UPWELLING AT CABO FRIO (BRAZIL)

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THESIS

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by

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ABSTRACT

The data at 2 fixed stations along an east-west section of the Brazilian coast near Rio de Janeiro show correlation between observations of wind, sea level, sea temperature and currents. Easterly winds are associated with low temperatures, low sea levels and westward currents. Minimum values of sea level and sea temperature are obtained in the summer and also in the winter. In the Fall the maximum values of sea level and sea temperature are observed.

Offshore observations show a maximum incursion of cold water (upwelling) over the continental shelf in winter (July cruise) and summer (November cruise); the minimum incursion of cold water is in the Fall (April cruise).

A geostrophic model shows a net transport in the same direction indicated by the data.

TABLE OF CONTENTS

LIST OF FIGURES

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I. INTRODUCTION

A. UPWELLING AT CABO FRIO

Upwelling regions represent less than 0.1% of the ocean surface but contribute half of the world's fish supply. This fact makes the study of upwelling particularly important, but, the importance is not limited only to fisheries. The study of upwelling represents the understanding of a mechanism that can be useful for other purposes as for example the forecast of oceanic conditions for sound propagation. Several studies have been conducted of coastal upwelling produced by the Peru, California, Benguela, Canary and other currents. This thesis gives a description of a significant but relatively unknown upwelling region on the Brazilian coast. It is not known who first recognized this upwelling zone but the navigators have known about it since the region was named Cabo Frio, which means Cold Cape.

Unlike the above currents the upwelling off Cabo Frio occurs on an east-west coast in a western ocean; however, the horizontal divergence here is also caused by the wind, favored by the baroclinic field on the continental slope and the bottom topography.

This work is based on data obtained mainly from August 1970 to July 1971 at two coastal stations, Rio De Janeiro and Cabo Frio. In addition, data from 6 oceanographic cruises about 3 months apart is included.

The first part of this thesis is an analysis of the data available showing relationships among the atmospheric and oceanic parameters involved. The second part applies a method of computation of flux transport and the resultant flow is compared with oceanographic data.

Figure 1 represents the region studied, showing bathimetric lines in meters.

II. ANALYSIS OF DATA

A. SOURCE OF DATA

The data used in this work comes from the following sources:

1. Instituto De Pesquisas Da Marinha - Brazilian Navy

Temperature at a depth of 25 meters, Rasa Island, off Rio De Janeiro, using thermograph from September 1970 to July 1971.

Temperature at a depth of 25 meters, Cabo Frio island, thermograph, from August 1970 to July 1971

Current off Rio De Janeiro at a depth of 20 meters measured during 8 days (April 1971). Current between Cabo Frio Island and the continent (5, 15 and 20 days, observed periods).

Tides at Cabo Frio from August 1970 to August 1971.

Hourly wind observation collected at Alcalis Plant, Cabo Frio, from August 1970 to July 1971.

2. Diretoria De Hidrografia E Navegação - Brazilian Navy

Cruise in September 1971, oceanographic ship 'Almirante Saldanha', 11 days of observations every 3 hours at latitude 22°56.5 south and longitude 041°54.5 west and 2 additional profiles.

Tides in Guanabara Bay, Rio De Janeiro, from August 1970 to December 1971.

Winds and atmospheric pressure at Rasa Island, from August 1970 to August 1971.

3. <u>Instituto Oceanografico, University of S. Paulo</u>

Six oceanographic cruises, from January 1970 to August 1971, the data was obtained by the oceanographic ship 'W. Besnard'.

B. METEOROLOGY

The atmospheric pressure at sea level is characterized at mid-latitudes of the South Atlantic Ocean by the presence of an anticyclone centered about latitude 25° south and longitude 10° west.

In the Cabo Frio region the distribution of isobars (Fig. 2 and 3) shows a lower value for pressure in summer than in winter. This agrees with the values obtained from monthly averages of atmospheric pressure at Rio De Janeiro (Fig. 4). It can also be seen in Figures 2 and 3 that from the pattern of isobars one can expect E to NE winds through the whole year. The above picture is disturbed at times by the passage of cold air masses from the south bringing southerly winds with duration from a few hours to less than 3 days in most cases. The curves in Figure 5 comes from coastal observations in Cabo Frio and the duration there does not neccessarily represent the duration of offshore southerly winds as the air masses may move away from the coast. This is an important fact because when studying interrelations between ocean and atmosphere one may note coastal variations in the ocean apparently in response to a southerly wind that is not always present at the point where the wind observation is made.

The meteorological observations offshore are very sparse. A brief study on atmospheric circulation was conducted using pictures taken from the satellite ATS-3. The method used consisted in following clouds trajectories. These cloud movements seem to be representative of the general circulation. It was felt the amount of work involved in analyzing a whole year of data and comparing the results with surface observation would be more appropriate for a separate paper. Therefore, the offshore wind for this thesis was represented only by data from ship board observations (Fig. 6.1 to 6.4). These observations are not necessarily synoptic but are very reliable at each point and suitable for the purpose of the present work. The 4 sets of data each constitute a 'snapshot' with an average duration of 3 days. This data is useful for comparing observed winds and the oceanographic parameters but does not permit an insight into the weather history. Therefore, the wind distribution for each cruise is shown for the time that data was available. This does not necessarily represent characteristic values for the particular month of the cruise. Two facts are noteworthy and those are probably representative of the general circulation. First, are the strong easterlies for August, which seem to be a representative flow. The reason for the greater intensity in that particular month is the greater gradient of pressure in winter (Ref. 1) toward the equator. Secondly, the pattern in all figures suggests a steady wind eastward of the meridian 43° degrees west and close to the coast a variable or undefined pattern exists to the west.

C. OBSERVATIONS AT FIXED STATIONS

1. Sea Temperature and Sea Level Variations

The temperature was obtained by thermographs, replaced by divers. These values are not as precise as the ones obtained by reversing thermometers. We can expect a maximum error of 0.3°C in the sea temperature. The observations were carried out almost continuously for the whole year and the variations of interest, that is, cycles of upwelling interrupted by warm water, are of one order of magnitude greater than the error. The temperature at Rio and Cabo Frio was averaged monthly and the results are shown in Figures 7 and 8.

a. Sea Level at Cabo Frio and Rio De Janeiro

The observations of tides were continuously recorded. Each day the values were checked against marks on a fixed pole nearby. Hourly readings were obtained from the strip charts and the sea level was calculated by applying a Doodson Filter (Ref. 2). There are filters of greater sophistication, but, the interest here is in relating sea level to winds and sea temperature at the low frequency range of oscillation, the Doodson Filter seems to be satisfactory for this purpose.

The atmospheric pressure has a direct effect on the sea level acting as an inverted barometer, the relationship between sea level and atmospheric pressure being that the pressure exerted by 0.995 cm of water is 1 mb. Patullo, et al, (Ref. 3) presents a listing of monthly pressures for

all oceans. If these values are subtracted from those observed at Rasa Island and the differences are averaged we find the maximum correction for sea level due to atmospheric pressure would be -6.2 cm in July and +3.3 cm in December.

Another necessary correction to sea level is for steric departures. These are departures caused by changes in density which cause changes in volume and consequently in height. This variation can be represented as

$$\Delta z = \frac{1}{g} \int_{p_a}^{p_o} \Delta\alpha \, dp \qquad (1)$$

where g = gravity, α = specific volume and p = pressure.

If we assume extreme variations of density and apply the above expression for the full depth of water we find a correction less than 1 cm for the steric effect, therefore, this effect will be neglected in this work.

Figures 9 and 10 represent monthly averages of sea level at Cabo Frio and Rio De Janeiro, respectively with corrections for the effect of atmospheric pressure. An annual oscillation with the double amplitude of approximately 40 cm can be seen at both places. The effect of atmospheric pressure on the sea level varies not only in time but also geographically, we do not have available a geographic distribution of pressure except for average values, but we can assume that the greatest pressure variations are brought about by cold air masses passing through the area. These variations are less than 10 mb over the hundreds of miles which the whole system involves. The data shows oscillations

of sea level sometimes greater than 50 cm following the passage of a cold air mass, therefore, the geographic effect will be relatively minor and will be ignored here.

2. Time Series of Wind, Sea Level, Temperature and Currents

The cross correlation function is defined as

$$\rho_{12}(u) = \frac{\gamma_{12}(u)}{[\gamma_{11}(o)\ \gamma_{22}(o)]^{\frac{1}{2}}} \qquad (2)$$

where γ_{11} (o) and γ_{22} (o) represent autocovariances for lag zero, γ_{12} represent cross covariance. The cross correlations were obtained using an IBM 360 computer and the number of lags did not exceed 10 percent of the total number of points available.

a. Cross Correlation of Wind and Sea Level

It was found that the wind changes precedes the sea level change by 6 hours (Fig. 11.1) with a correlation coefficient of 0.45. This lag is reasonable considering that the wind stress is responsible for variations in sea level. The east-west component of the wind was the parameter used in the above correlation and it is seen from the data that the velocity of the easterly wind begins to decrease before the passage of a cold air mass. The wind direction shifts to the west after the passage of a cold air mass. The initial decrease in velocity is followed by an increase in sea level. Therefore, the sea level begins to increase before the passage of a cold air mass. This fact could lead an observer

sensitive only to wind changes from east to west to the erroneous conclusion that the sea level rise at these coastal stations always precedes a wind field change at the same point. In some cases the sea level starts rising more than 24 hours in advance the passage of a cold air mass. This suggests that the sea level could be used to forecast cold air masses which might be most helpful when the changes in the wind field occurs away from the coast. However, the weather in the region is not fully understood, in some cases it was noted that an increase in sea level occurred after which the westerlies did not appear at the coast or they appeared for just a few hours. This suggests that the coastal stations at Rasa Island and Cabo Frio are not always representative of the wind field offshore.

The observed rise in sea level which occurs with a decrease in the velocity of the easterlies can be attributed to a lessening of the stress of the easterlies which moves water away from the coast. This decrease in intensity is followed by a decrease in the seaward slope and consequently a rising in sea level at the coast. An additional rise in sea level could be brought about only by the piling up of water along the coast due to westerly or southerly winds.

b. Cross Correlation Between Sea Level At Rio De Janeiro and Cabo Frio

A cross correlation was carried out between the sea levels at Rio De Janeiro and Cabo Frio. A peak was found

[illegible]

for a lag of 5 hours; the sea level change in Rio De Janeiro preceding Cabo Frio (Fig. 11-2). However, the hourly sequence of events suggest coincidence in time when the sea level is above average at both points. A phase angle always occur for below average values of sea level. Therefore an average sea level was obtained and cross correlations were made separately for periods of sea level above and below average. The result was a maximum at zero lag for periods of sea level above the average and about 5 hours when the sea level was below the average. These results suggest a simultaneous response for westerly winds or a decrease in intensity of the easterlies. In addition, the sea level in Rio De Janeiro presents an earlier response to easterlies than occur at Cabo Frio.

c. Cross Correlation Between Sea Level and Temperature at Cabo Frio

The cross correlation between sea level and temperature is shown in Figure 11.3. Sea level changes precede temperature changes by 40 hours, with a cross correlation coefficient of 0.8.

d. Sea Level and Currents

Observations of currents were carried out continuously for a period of 20 days. The data consists of instantaneous direction and integrated velocity every 5 minutes. These values were vectorially summed for each hour and the results compared to sea level in the same period.

A maximum cross correlation coefficient of 0.76 was found for zero lag. The spectra distribution is shown in Figure 12. The maximum lag used corresponds to 5% of the total number of points. The minimum frequency calculated corresponds to a period of approximately 100 hours. It can be seen that the spectra for both observations shows a maximum toward low frequencies, for periods greater than 30 hours; the spectra of currents shows a secondary maximum at a period of approximately 12.5 hours which is clearly the tidal influence. The coherence also shows a maximum at low frequencies with a phase angle not far from zero over that range. The results shows a strong relationship between currents and sea level. The tidal effect seems to play a secondary influence on the observed points.

A similar analysis was carried out for observations of currents in a point located 3 miles off Rio De Janeiro. It was found a maximum correlation for zero lag.

These results suggest the existence of a westward flow along the coast for upwelling conditions and a counter current, or an eastward flow along the coast, for situations of sea level above average.

e. Variation in Sea Level Along the Coast

There is no geodesic leveling between the tide gauge in Cabo Frio and that in Rio De Janeiro, therefore a comparison of sea levels represents a relative difference. These differences were averaged, positive and negative values were obtained in relation to this average.

A positive difference was found (the sea level at Rio greater than the sea level at Cabo Frio) when the sea levels at both stations were above average. On the other hand, a negative difference was found when the sea level at both stations were below average. This result suggest a higher sea level at Cabo Frio than at Rio for upwelling conditions, and a higher sea level at Rio than at Cabo Frio when the water is piled up against the coast.

D. OFFSHORE DATA

1. T-S Diagram

A typical T-S diagram for the area is shown in Figure 13 which represents water masses up to approximately a depth of 300 m.

It can be seen that curve A consists of almost a straight line from T=22°C, S=36.70°/₀₀ to T=12°.4C S=35.1°/₀₀. Several T-S diagrams have been traced and the principal departures from curve A are the following:

(a) An extension to higher temperatures and Salinities for the surface layers, represented by curves B.

(b) Detachment of surface layers over the continental shelf, represented by curve C. These detachments occur in the stations close to the coast and seem more pronounced in the upwelling region or in the region of upwelled water transport.

(c) Bottom mixed layers represented by one point in the T-S diagram, these layers have been found in the region delimited by the dashed line, curve D. This mixed water seems to be closely associated with the advection of upwelled water.

2. Temperature at Surface

The temperature distribution at the surface is presented in Figures 14.1 to 14.6. The pattern is characterized by a minimum temperature close to the coast, approximately at 23° south and shifting from 042° 45' W to 042° 10' W. It will be shown below that this low temperature is caused by upwelling.

The minimum temperature can also be seen to extend, increasing its value, to the southwest.

Another feature is the maximum temperature to the east, in the area where the Brazil current flows. This maximum cannot be followed further south because the current flows just off the continental slope and the stations do not extend far enough into that region. The maximum sea surface temperature values obtained from the available data were 28°C in February and 23°C in July.

3. Temperature at the Bottom

The data used to analyze bottom temperature was taken from the deepest Nansen bottle at each station, the values were discarded when the sample distance above the bottom exceeded 10 m. Most of the observations used were taken at approximately 5 m above the bottom.

The lowest temperature was obtained in January (Fig. 15.1), at approximately 042° 30' W. Figure 15.2, in February, shows a minimum temperature just off Cabo Frio, with a positive gradient in the NW direction toward the coast. It is seen also that about 42° 50' W the axis of positive gradient shifts to SW, tending away from the coast. Figure 15.3 representing stations approximately 5 days later than those in Figure 15.2 shows the axis of minimum temperature with a small displacement offshore. Additional data eastward of 42° W shows higher temperature in that area also. Figure 15.4 for April, also shows lower temperatures along the coast in a pattern similar to the above pictures, but the gradients are weaker. Figure 5 for July, shows a very pronounced pattern with the minimum temperature axis presenting a positive gradient initially to NW and thereafter changing to a direction parallel to the coast. Figure 51.6 for December, presents basically the same distribution as Figure 15.5.

As we have mentioned previously, the above pictures were obtained for each available cruise and do not necessarily represent characteristic values for the particular month. However, the lower temperatures in July and November coincides with a lower sea level for those months. All figures suggest a flow of cold water in the NW direction off Cabo Frio, this water seems to be closest to the coast at approximately 042° 30' W. After this point the water seems to go in a direction between W and SW.

4. Vertical Profiles Perpendicular to the Coast

Figure 16.1 shows the geographical location of vertical profiles presented in Figures 16.2 to 16.9. Due to the greater variation in the vertical than in the horizontal directions the corresponding scales in the profiles are different.

Profile 1, east of Cabo Frio, shows startification, no mixing and relatively high temperatures at the bottom.

Profile 2, along the meridian passing over Cabo Frio, shows a rising of the 12°C isotherm from 400 to 130 meters. This is the lowest value isotherm found over the continental shelf in the above profiles. The Profile 3 shows the rising of the 13°C isotherm toward the continental shelf and stratification at the bottom. Profile 4 shows an isolated minimum over the continental shelf. As the profiles proceed westward the minimum increase its value from 12°C at the Profile 2 to 14.5°C at Profile 7. The increase of bottom temperature from Profile 2 to Profile 1 is much greater, this might suggest a different system.

Profile 4A represents isopicnicals for the same profile shown in Profile 4A, the comparison of the two profiles shows that the minimum temperatures coincides with the maximum density. This should not be more surprising than a comparison of parameters. However, it is not easy to think of a more dense water staying above the continental shelf without sinking down in response to gravitational forces. This unstable situation could be maintained only as a result of a current up onto and along the continental shelf.

The above sequence of profiles suggests upwelling in the region of Profiles 2 and 3. The upwelled water moves westward over the continental shelf, increasing in temperature and mixing at the bottom.

5. Vertical Profiles Along the Coast

The profiles are drawn for the November cruise. Figure 17.1 represents a profile parallel to the coast in the east-west direction, approximate latitude 24° 10' S. Figures 17.2 and 17.3 also represent profiles parallel to the coast at approximately 23° 55' S and 23° 35' S respectively.

It is difficult to follow water masses in the above figures. In Figure 17.1 the coldest water is on the left and in Figure 17.3 is on the right side, this might lead to the erroneous conclusion that cold water is approaching the coast in a NE direction. The reason for the shift in location is simply because in Figure 17.1 the left side is over the continental shelf and the right side is over the deep water. This suggests a topographic effect. In an attempt to eliminate this effect the profiles of Figures 17.4, 17.5 and 17.6 were drawn along depth contours of 150, 100 and 60 meters, respectively. These figures show clearly the existence of a cold water ridge oriented in the NW-SE direction, with increasing mixing to the west. These results agree with the ones shown by the profiles perpendicular to the coast and also show a dependence of the upwelling on the bottom topography.

6. Topography of 13°.5C Isotherm

To obtain another view of temperature distribution, the depths of the 13.5 isothermal surface were plotted in Figures 18.1 to 18.6.

Figure 18.1 for January, shows the 13°.5C isotherm at depths exceeding 200 m off the continental slope. The isolated isotherms close to the coast probably have their origin in past upwelling. Figures 18.2 and 18.3 present the isothermal surface at shallower depths than in January. Figure 18.4 for April, shows the deepest topography of all cruises, this suggests an agreement with the highest sea level found in April. Figures 18.5 and 18.6 in July and November, show the shallowest layers for the isotherm. Also, this contour suggests an upward movement in the NW direction.

7. Volumetric Analysis

In order to obtain a representation of amounts of various water masses present and also changes in them, a calculation was carried out of water volumes characterized by temperature and salinity. The T-S diagram was divided into intervals of 0.2°C and 0.5‰ and the volumes were plotted for each square. Each square was referred by its central temperature, salinity or both.

Figures 19.1 and 19.2 represent the distribution of volume from the surface to 200 meters for April and November respectively. In April there is a maximum for a temperature of 24°C and another for 17°C. The April

maximum at 25°C seems to shift in November to 23°C and is not so well mixed. Also, the November surface water seems to have higher salinity and a lower temperature value than in April. The April maximum at 17°C seems to be replaced, the latter shows more mixing in November than in April. In November a large volume of water appears at 13°C.

Figures 19.3 and 19.4 shows the volumetric distribution of water masses to 100 m. The patterns are similar to the ones for 200 m.

From the figures we can say that in April the amounts of water are approximately uniformly distributed, except for a peak at 15°C. In November a pronounced peak appears at 23°C and another even higher at 15°C. These results suggest a greater distinction between water masses during the regime of upwelling.

III. A DETERMINATION OF RELATIVE FLOW IN SHALLOW WATER

The method used for determination of dynamic topography is based on the calculation of the baroclinic field, assuming the existence of a region deep enough for the barotropic and baroclinic fields to cancel each other. The sea surface slope is determined from the barotropic field and the circulation in lower layers can be determined by the thermal wind equation. The method requires the determination of a layer of no motion. It is relatively simple to make assumptions of no motion in deep water, but, in shallow water the assumptions are difficult to apply.

Presented below is the application of a method consisting basically of following stream functions along contours of constant f/d. Where f=coriolis force and d=depth;

A. THEORY

Assume an ocean model, geostrophic and hydrostatic,

$$\rho\ f\ v = \frac{\partial p}{\partial x} \qquad (3)$$

$$\rho\ f\ u = -\frac{\partial p}{\partial y} \qquad (4)$$

$$-\ \rho\ g = \frac{\partial p}{\partial z} \qquad (5)$$

The integration of the Horizontal equations, from the surface to the bottom, followed by cross differentiation and subtraction, assuming also constant atmospheric pressure and net divergence equal to zero, leads to the vorticity equation (6).

$$M_y \frac{\partial f}{\partial y} = - (\frac{\partial p_d}{\partial x} \frac{\partial d}{\partial y} - \frac{\partial p_d}{\partial y} \frac{\partial d}{\partial x}) \qquad (6)$$

The pressure gradient term can be represented by

$$\frac{\partial p}{\partial (x,y)} = \frac{\partial}{\partial (x,y)} \{g \int_z^o \rho \, dz\} + g \, \rho s \frac{\partial \xi}{\partial (x,y)} \qquad (7)$$

The total geostrophic transport, the baroclinic and barotropic transport, may be presented by

$$M_x = -\frac{g}{f} (\frac{\partial \beta}{\partial y} + \alpha_d \frac{\partial d}{\partial y} - \rho_s \, d \frac{\partial \xi}{\partial y}) \qquad (8)$$

$$M_y = \frac{g}{f} (\frac{\partial \beta}{\partial x} + \alpha_d \frac{\partial d}{\partial x} - \rho_s \, d \frac{\partial \xi}{\partial x}) \qquad (9)$$

where

$$M_x = - \frac{\partial \psi}{\partial y} \quad (8a) \qquad M_y = \frac{\partial \psi}{\partial x} \quad (9b)$$

Substituting (7) in (6) and applying relations (8), (8a), (9) and (9a) one determines after some manipulation:

$$J\ (\psi,\ f/d) = \frac{g}{d} J\ (\alpha_d, d) - \frac{g}{d^2}\ J\ (\beta, d) \qquad (10)$$

where

$$\alpha_d = \int_d^o \rho dz \qquad \beta = \int_o^d \alpha dz$$

B. APPLICATION

Equation (10) was solved for data collected by the oceanographic ship 'W. Besnard'. The equation was obtained from derivations using X, Y and Z axis, but the equation is expressed in Jacobians and this result is not dependent on the coordinate system. Therefore, the natural coordinate system described by Haltiner and Martin was applied. A constant value was assumed for the coriolis force. In

these circumstances equation (10) can be seen as representing advection of stream functions along isobathimetric lines.

The data used consisted of 4 profiles perpendicular to the coast and the values at constant depths were obtained by interpolation. The integrations were performed by computer applying a method of combination of Simpson's and Newton's rule. The differentiation were carried out manually using the method of central differences. The resultant distribution of stream lines is represented in Figure 20

IV. SUMMARY AND CONCLUSIONS

The meteorological regime in the south Atlantic Ocean shows, at western subtropical latitudes, the existence of winds with ENE direction. The Brazilian coast shifts to an east-west direction at Cabo Frio, this orientation of the coast in relation to the prevailing easterlies favors offshore transport of water in the surface layers. Westerly winds cause an opposite effect of onshore transport.

The data shows that, for the period between July 1970 and July 1971, two maxima of upwelling are present, for the summer (November to January) and August, respectively. The maximum of upwelling in the summer is caused by a predominance of easterlies with a minimum of winds with westerly component. The other maximum of upwelling, for August, is probably caused by an intensification of the easterlies; this intensification is expected as a result of a greater gradient of atmospheric pressure in the north-south direction caused by a maximum in pressure at the region in winter. However, this intensification of the easterlies is not clearly shown by the data available; the possible reason could be that the point of wind observation at the coast is not always representative of the wind offshore.

Associated with the easterlies seems to be a westward current along the coast, the sea surface topography increasing

to the east and seaward. Westerly winds have the opposite effect of piling up water against the coast, the sea surface topography seems to increase westward and shoreward, associated with this feature seems to be the existence of a current flowing to the east along the coast.

The cold water ridge approaches the coast from southeast up to about 30 miles west of Cabo Frio, after this point the cold water seems to be advected over the continental shelf with increasing bottom mixing, in a direction between W and SW. The average sea temperature at Cabo Frio is lower than at Rio, this could be caused by a lateral component of the cold water intrusion but the distance between stations precludes further analysis. Also, the low temperatures at Cabo Frio are favored by the bottom topography, the cape is the point where the continental shelf is narrowest and the isobathimetric lines are closest to the coast. Mentioned above was the eastward current associated with piling up of water along the coast, this current could cause the upwelled water to go to the east and Cabo Frio would possibly have cold present water for longer period of time.

The model shows a net transport crossing the bathymetry in the same direction obtained from the data. The values presented are relative to a water transport flowing initially along the bathy metry, northeast of the cape. An absolute transport could be obtained if the initial flow were measured.

V. SUGGESTIONS FOR FURTHER STUDIES

The data used in this work extend for a period of one year, from August 1970 to July 1971. A continuation of these observations will give annual variations and better understanding of the dynamics involved.

A greater amount of data on currents would be desirable, at different layers along the cold water intrusion and near the cape. The area seems to be suitable for studies of several oceanographic features, among them can be mentioned: nutrients available in the euphotic zone, primary productivity, mixing, advection, convections and ecology.

The oceanographic station should extend farther offshore allowing a study of the circulation off the continental slope. Near Cabo Frio a smaller distance between stations seems to be desirable.

Observations of temperature at fixed stations were initiated in a regular basis after 1970, the relationship between these results and sea level might possibly give an index of upwelling, based solely on the sea level and this index might be useful for hindcasting in periods before 1970.

A study of the stress of the wind on the surface layers and the effects of bathimetry and the coast, will give a better understanding of the forces involved. The author is working on the utilization of the Hansen Model in the region, the results will be presented in a separate paper.

Several models of upwelling in north-south coasts use the beta-effect, that is the variation of Coriolis with latitude. The Cabo Frio region seems to be particularly interesting in applications of models where the beta-effect is neglected.

Also, a better understanding of the wind circulation offshore is badly needed.

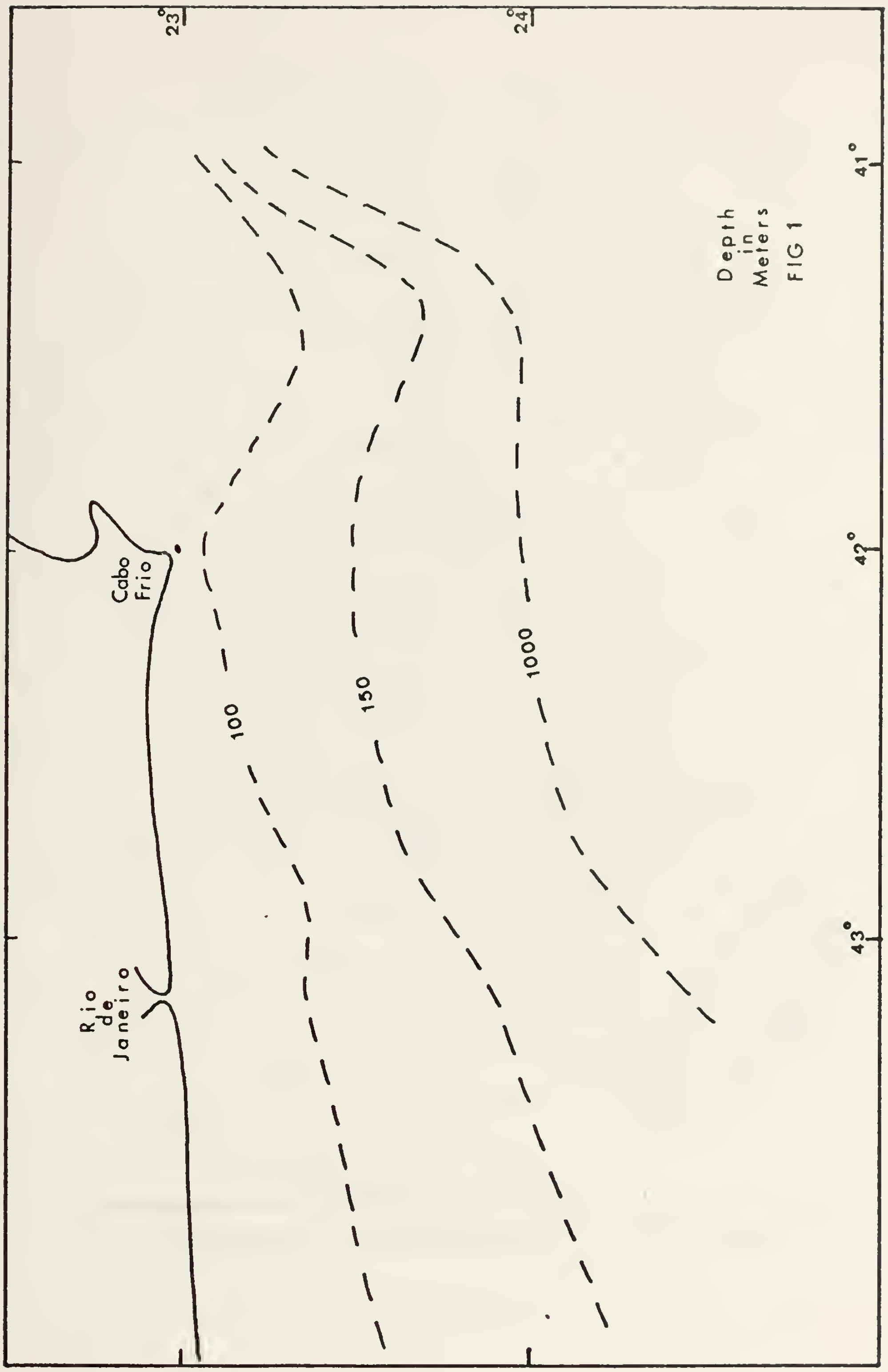

23°
24°
41°
42°
43°
Rio de Janeiro
Cabo Frio
100
150
1000
Depth in Meters

FIG 1

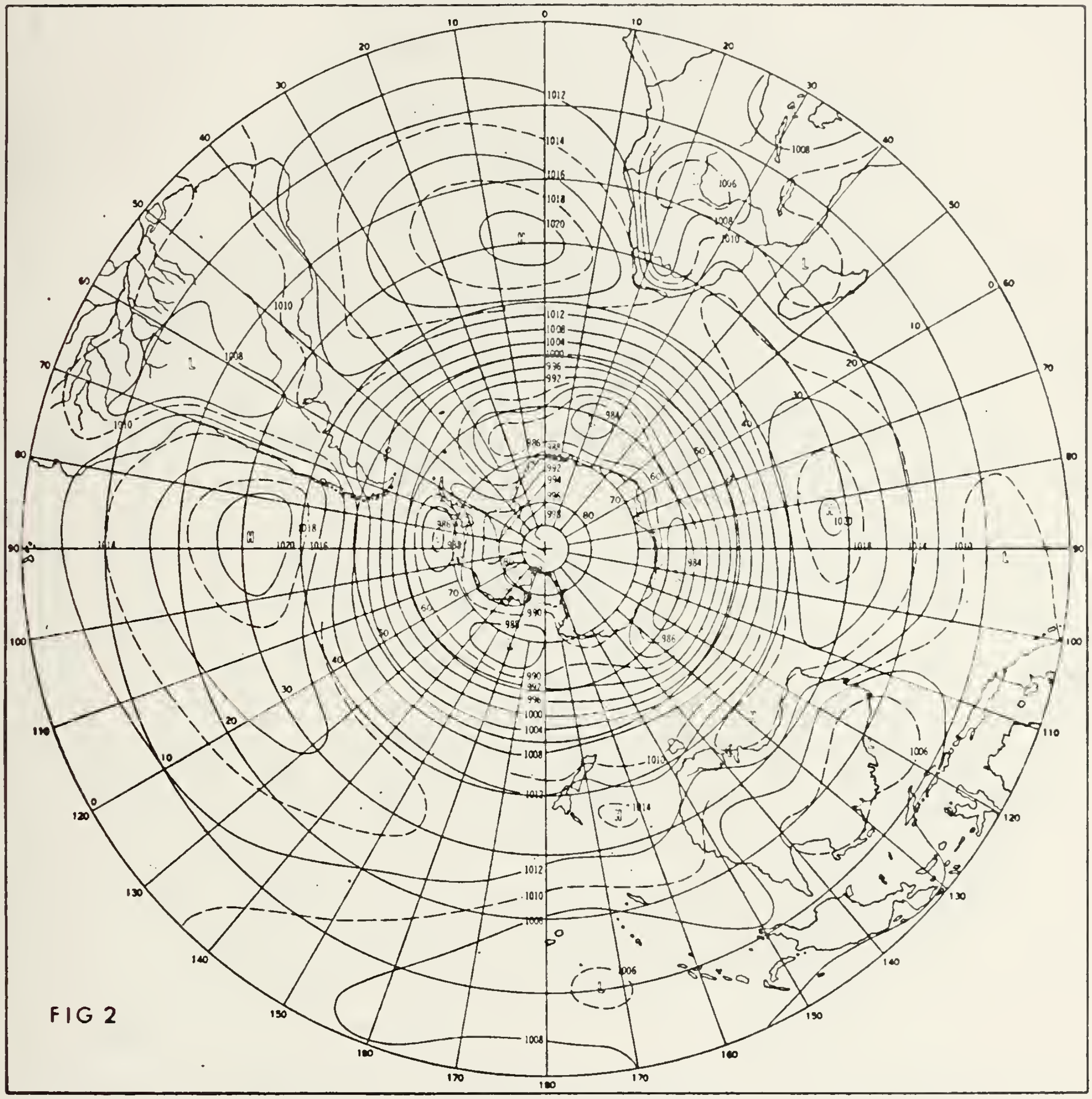


FIG 2

FIG. 4.1. Mean pressure (mb) at sea level in January. (From Taljaard *et al.*, 1969.)

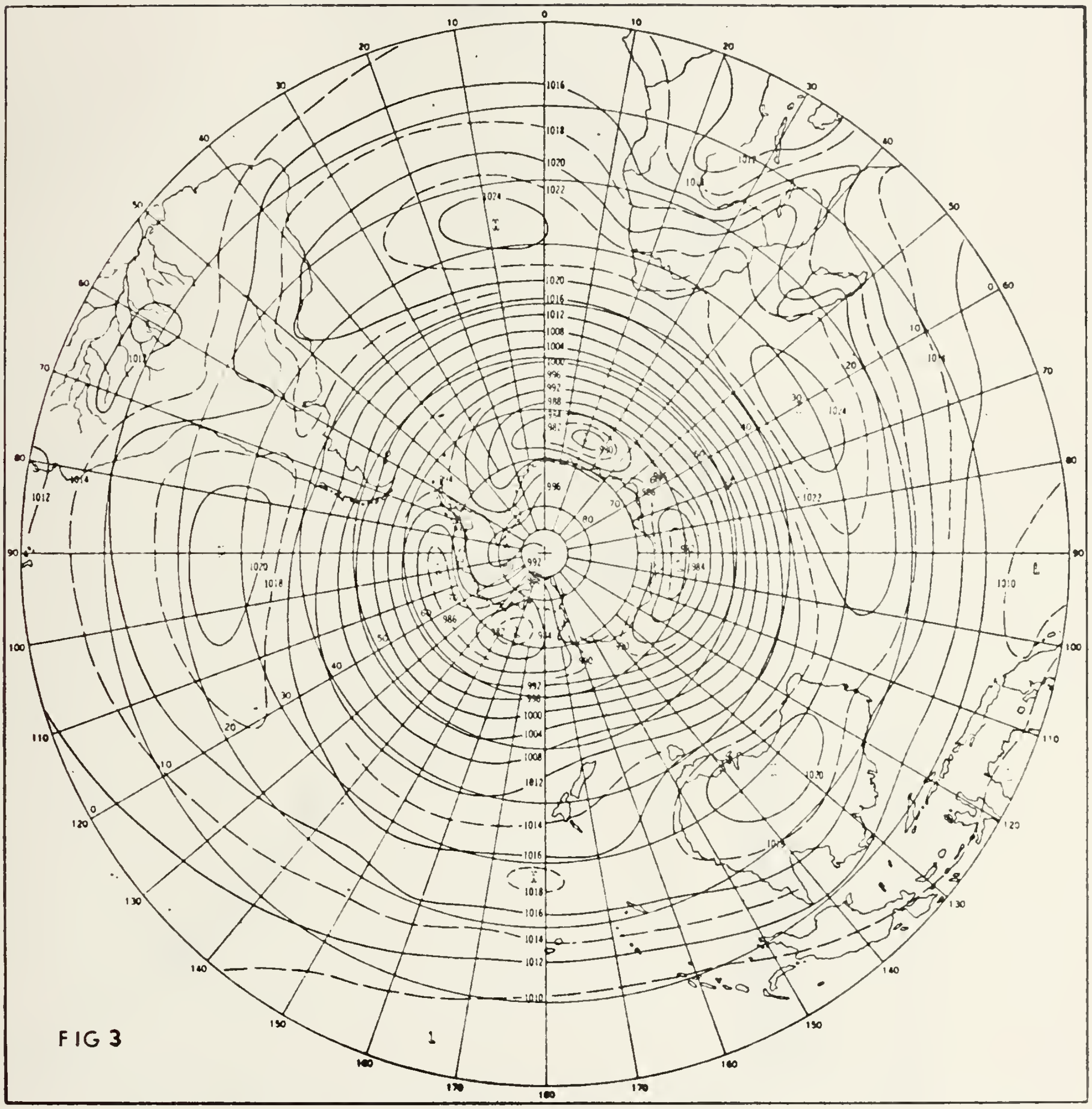
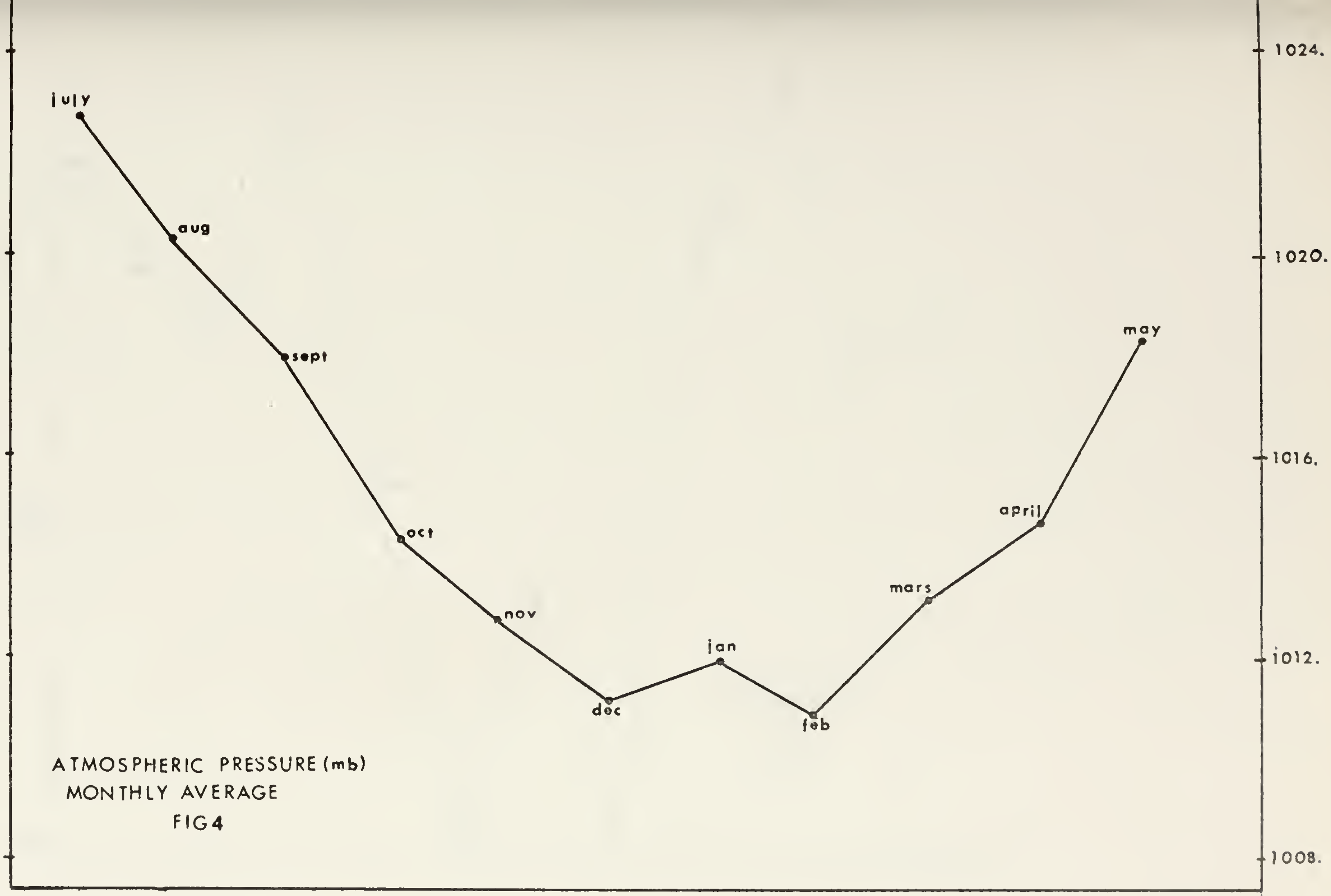
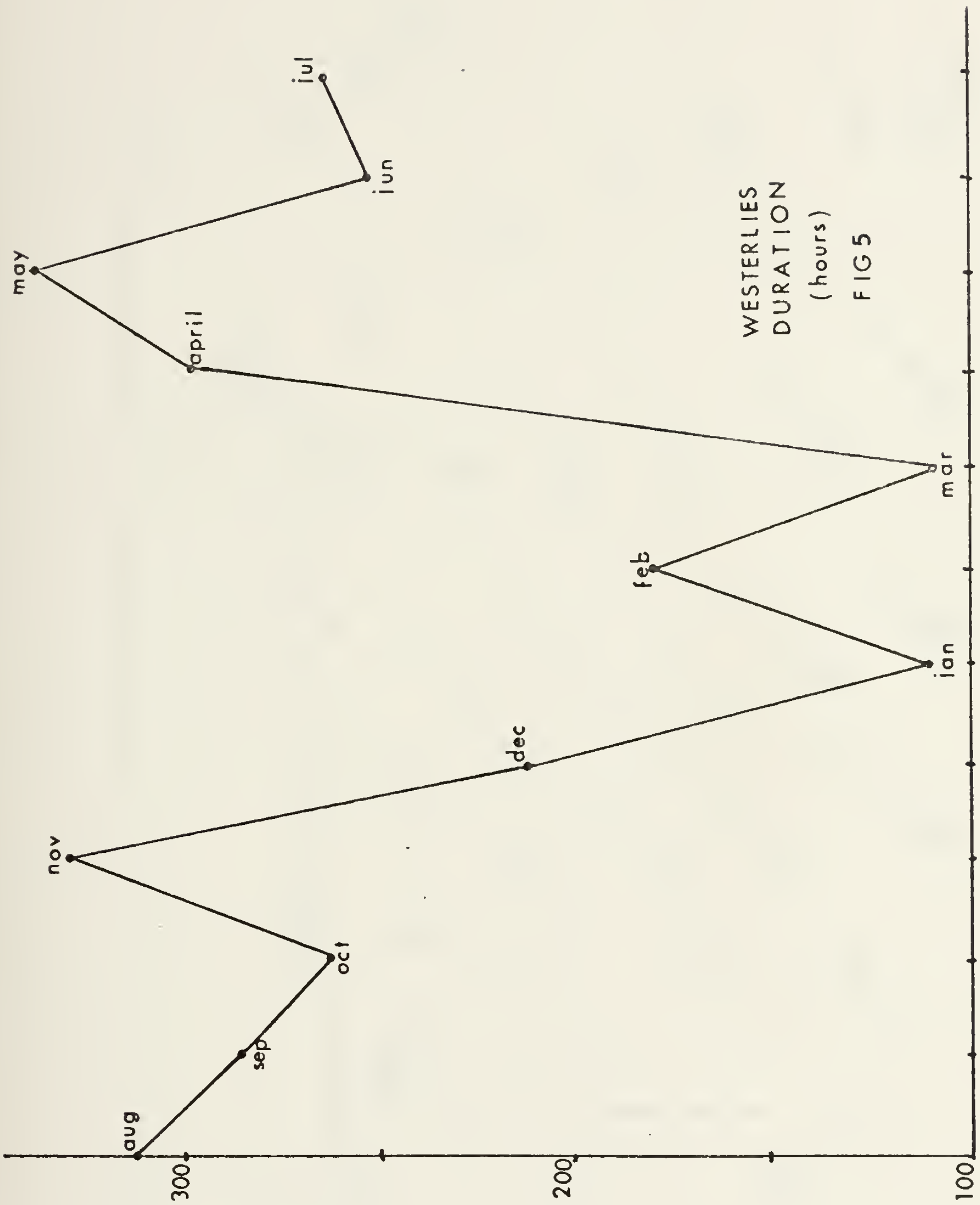


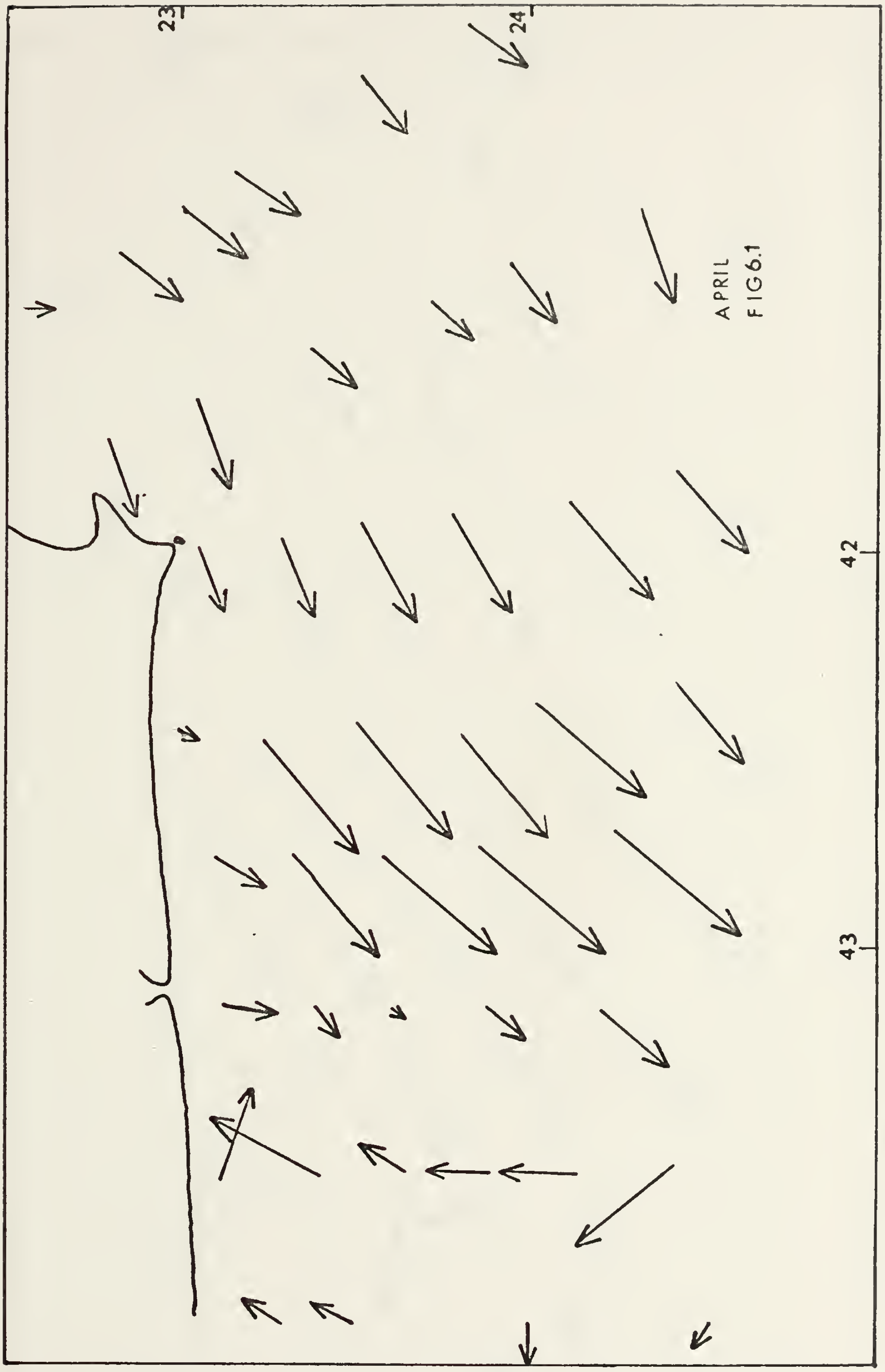
Fig. 4.2. Mean pressure (mb) at sea level in July. (From Taljaard *et al.*, 1969.)



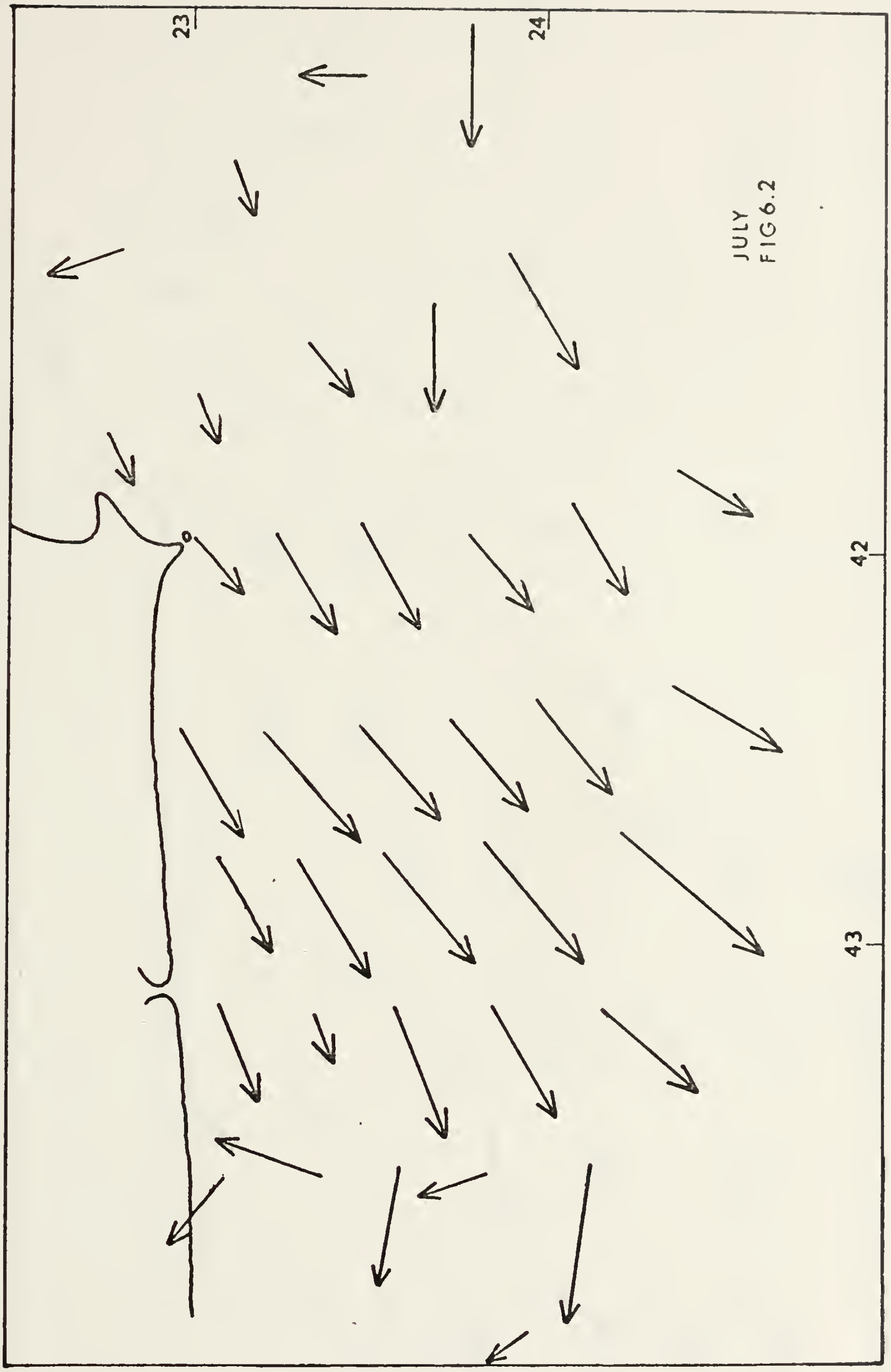
ATMOSPHERIC PRESSURE (mb)
MONTHLY AVERAGE
FIG 4



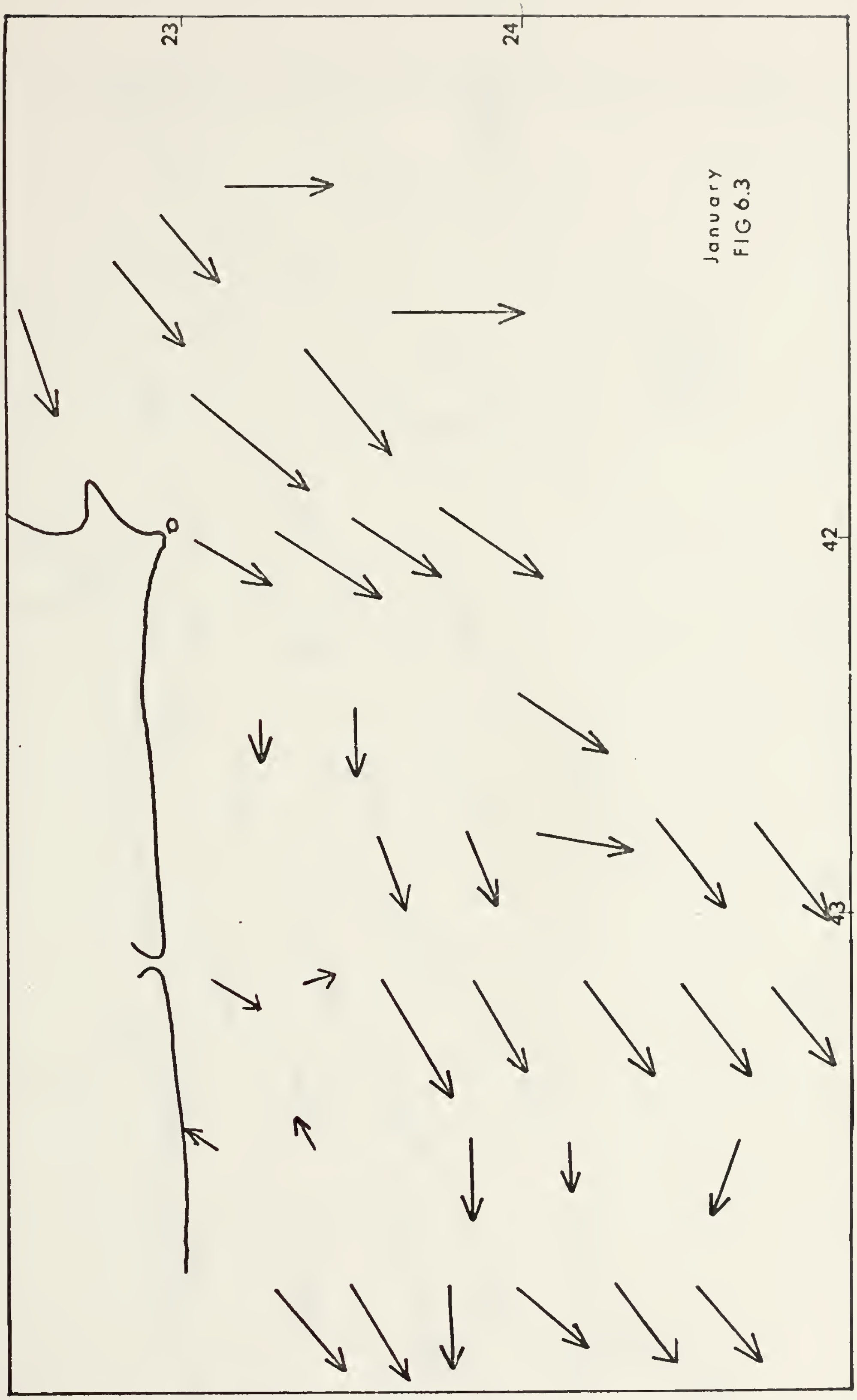
WESTERLIES DURATION (hours) FIG5



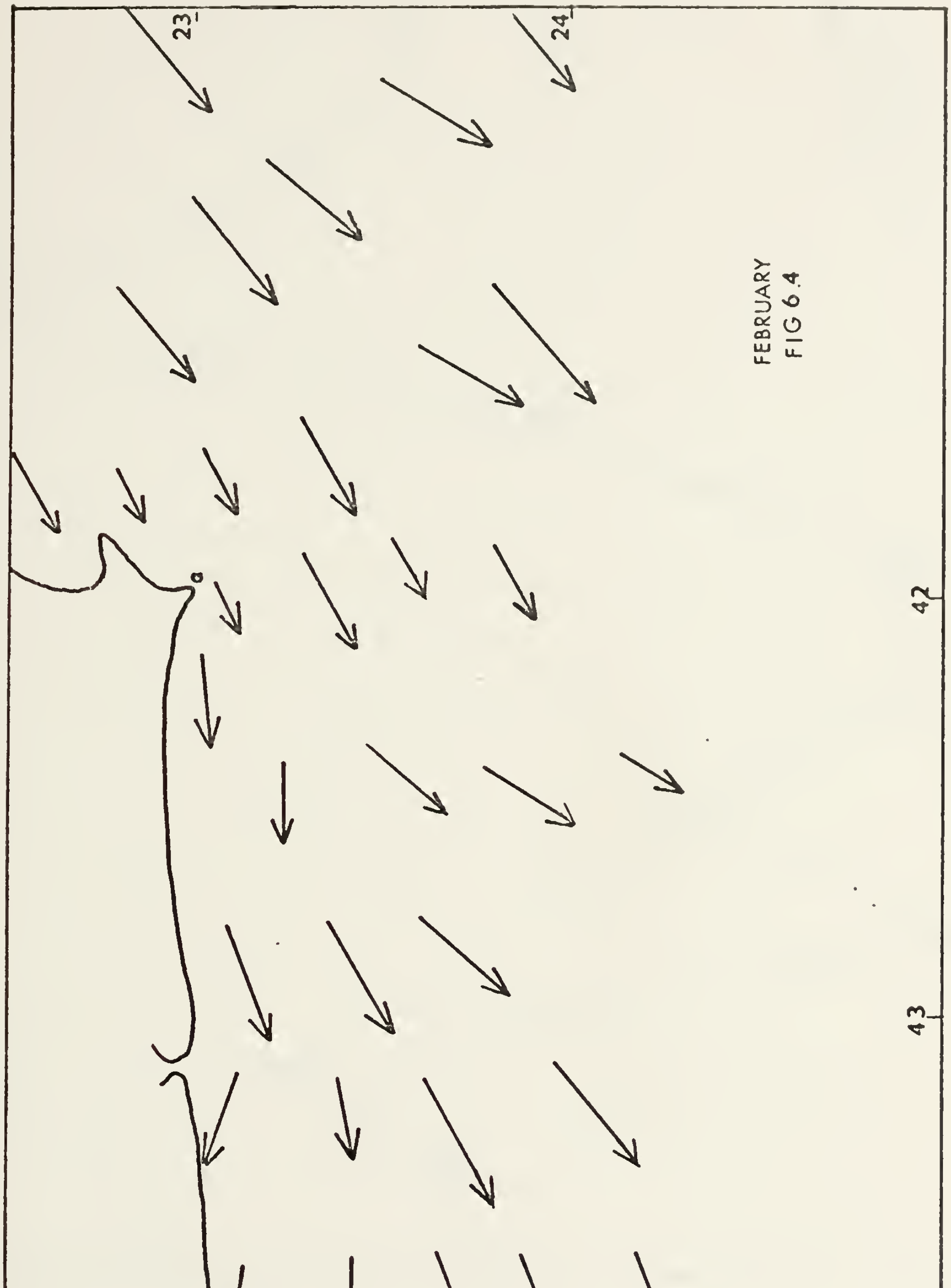
APRIL
FIG6.1



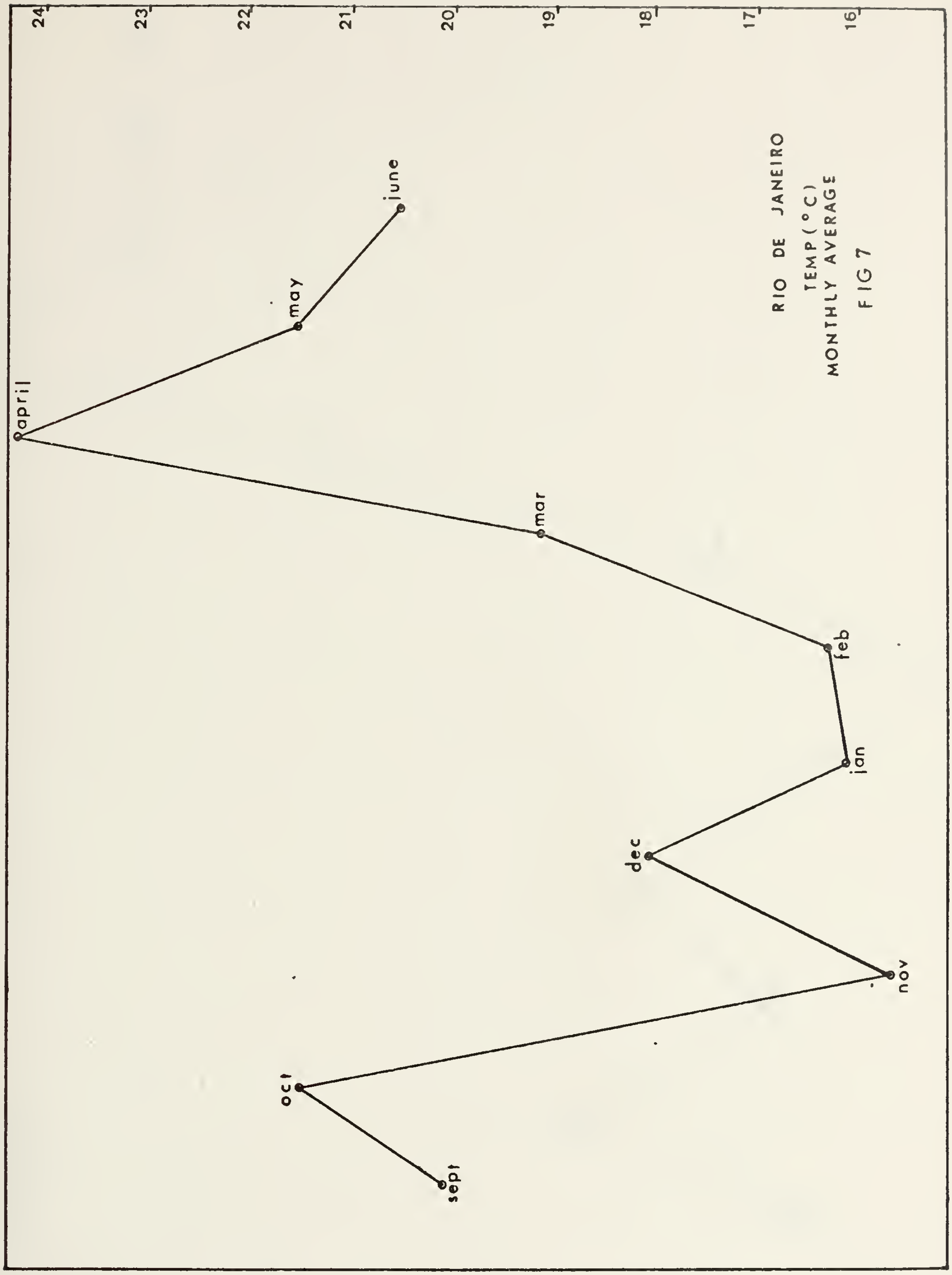
JULY
FIG 6.2



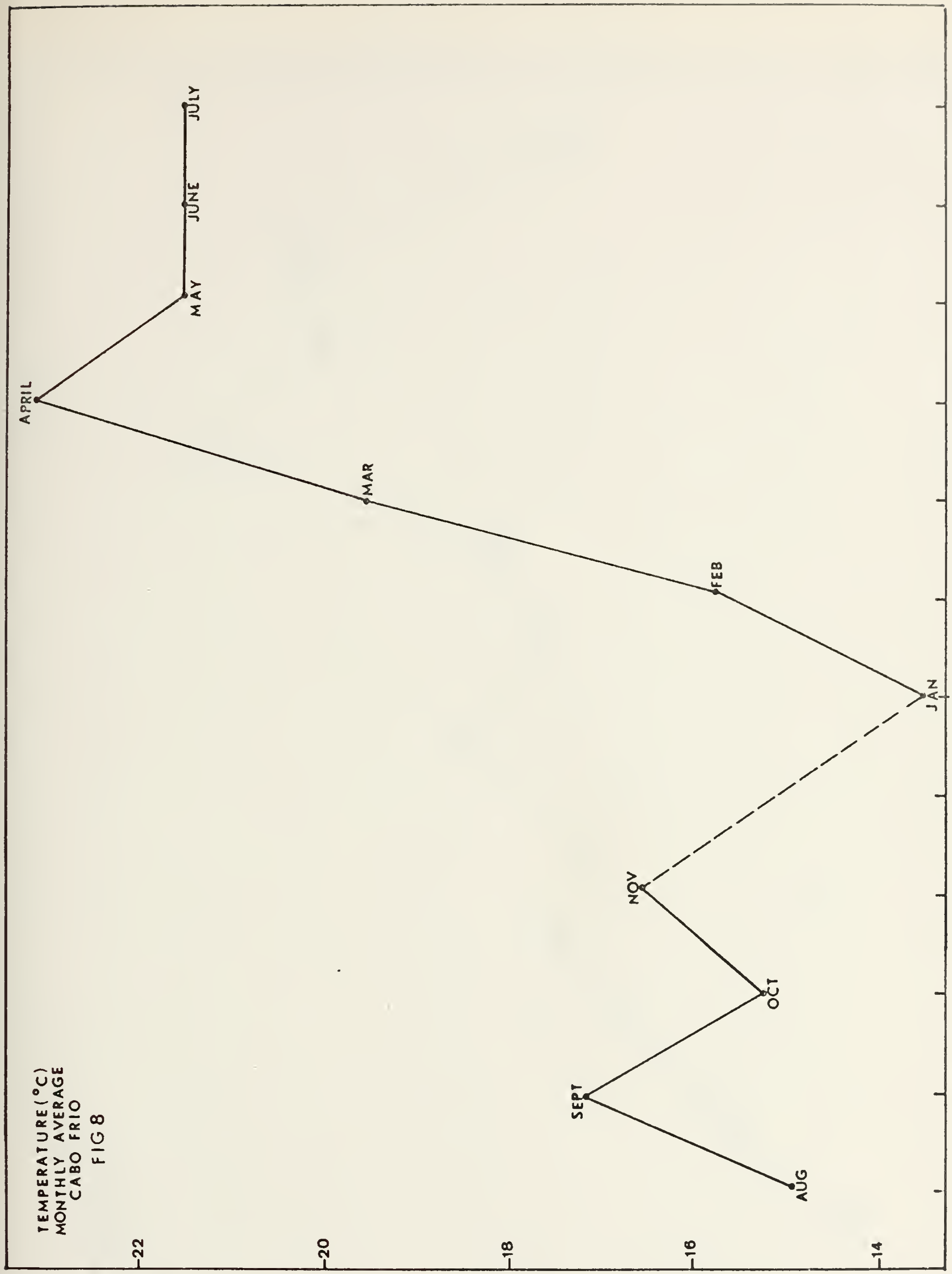
January
FIG 6.3

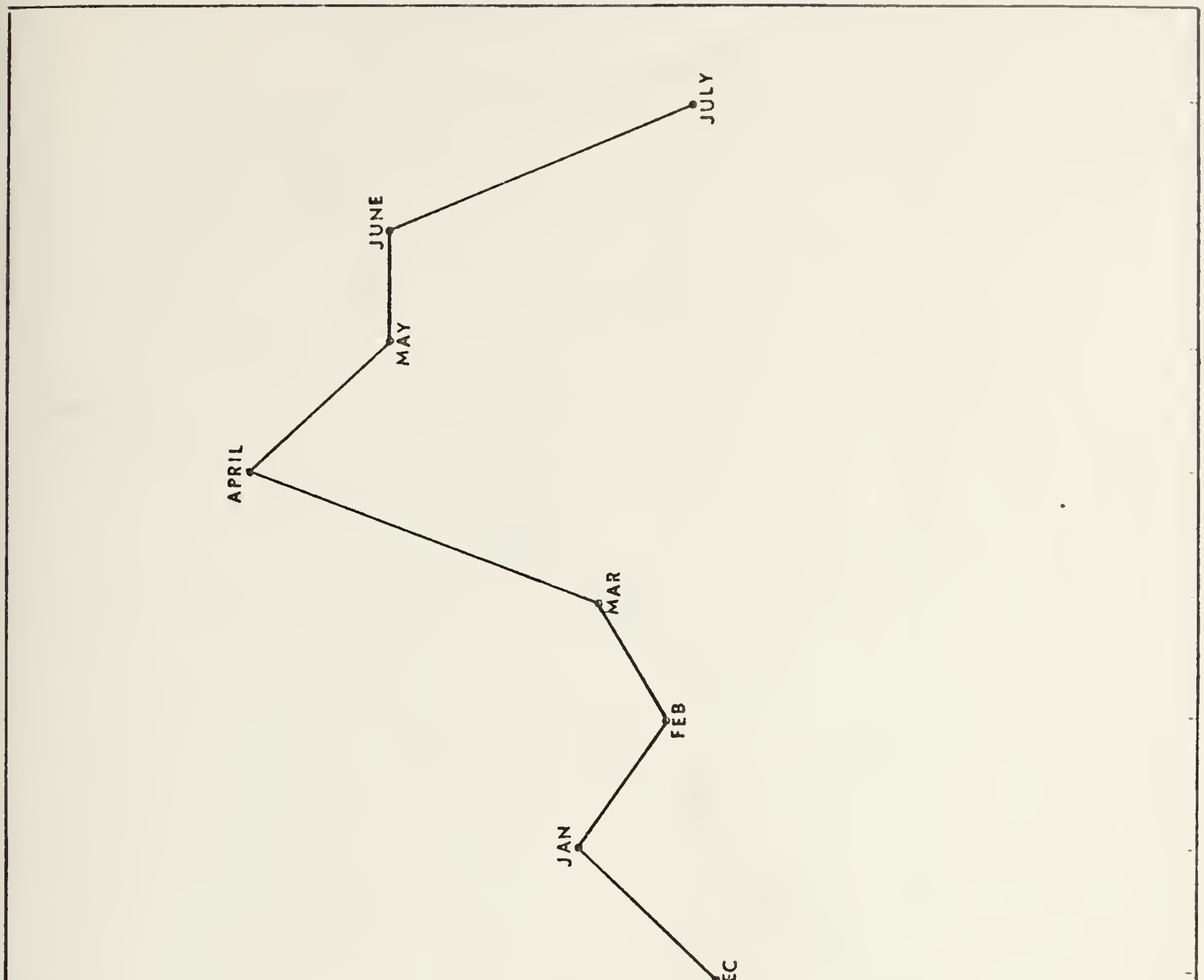


FEBRUARY
FIG 6.4

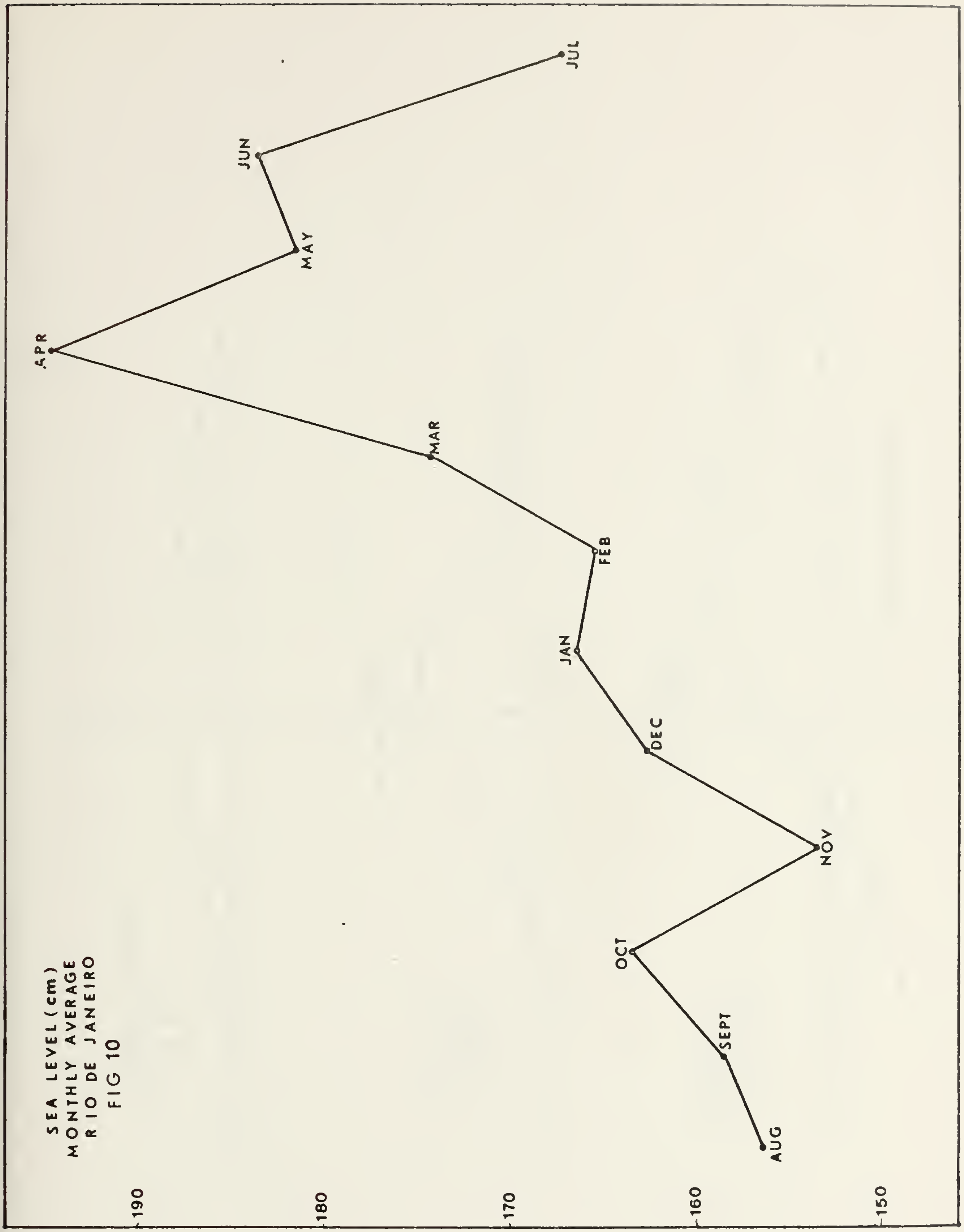


RIO DE JANEIRO
TEMP (°C)
MONTHLY AVERAGE
FIG 7

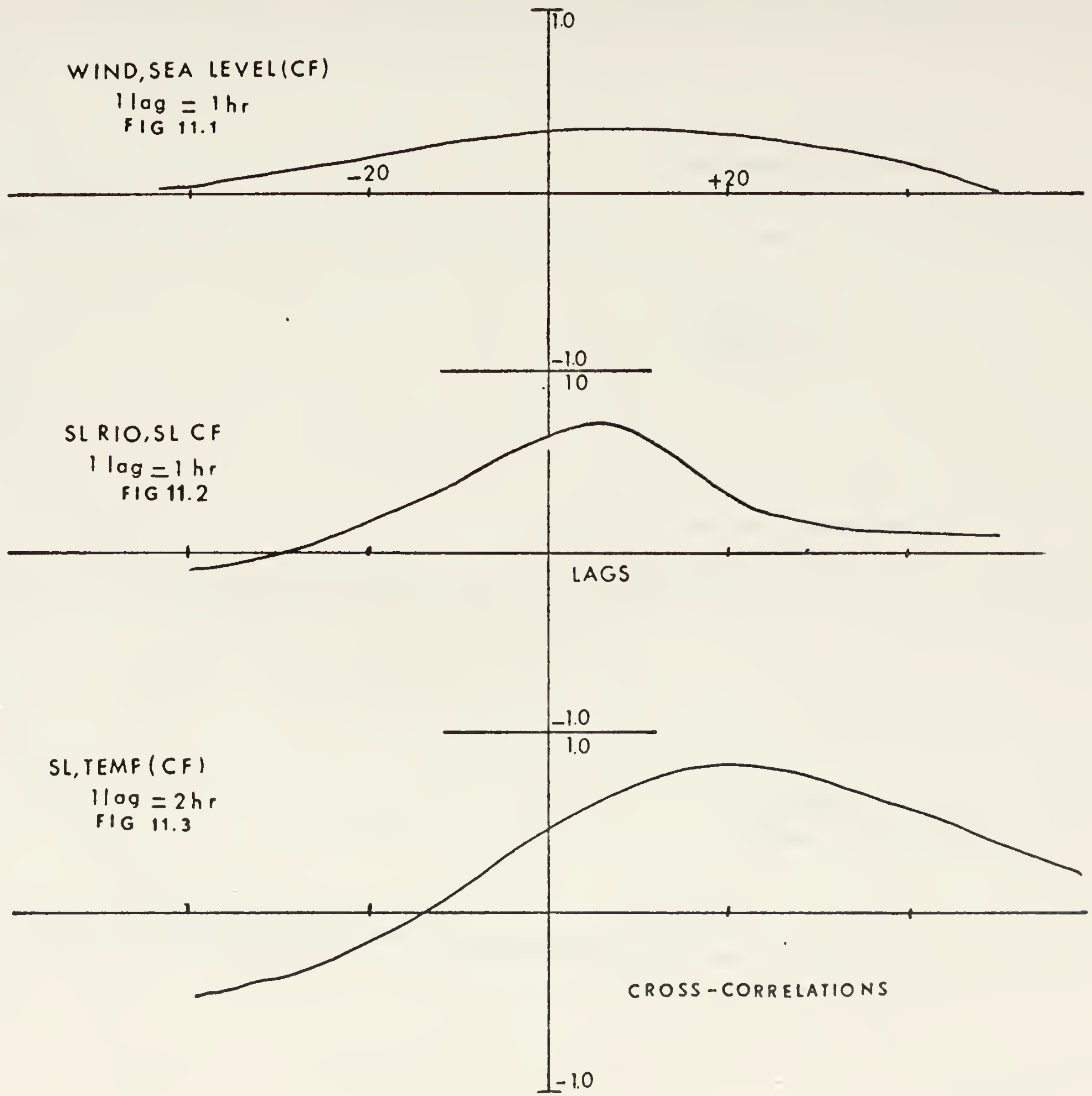

TEMPERATURE (°C)
MONTHLY AVERAGE
CABO FRIO
FIG 8
22
20
18
16
14
AUG
SEPT
OCT
NOV
JAN
FEB
MAR
APRIL
MAY
JUNE
JULY



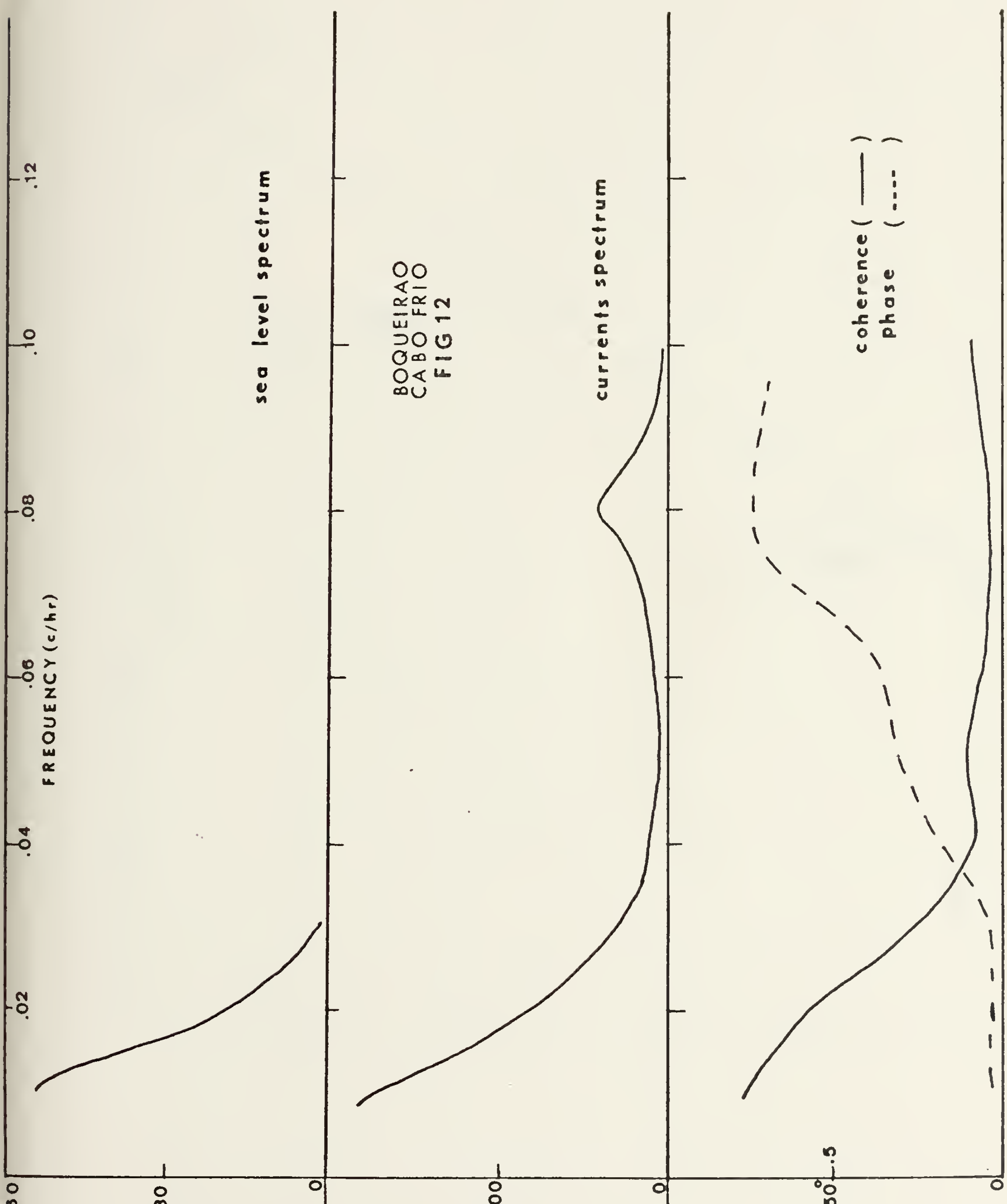
SEA LEVEL (cm)
MONTHLY AVERAGE
CABO FRIO
FIG 9



SEA LEVEL (cm)
MONTHLY AVERAGE
RIO DE JANEIRO
FIG 10



CROSS-CORRELATIONS


FREQUENCY (c/hr)
.02
.04
.06
.08
.10
.12
60
30
0
200
0
50°
.5
0
sea level spectrum
BOQUEIRAO
CABO FRIO
FIG 12
currents spectrum
coherence (——)
phase (----)

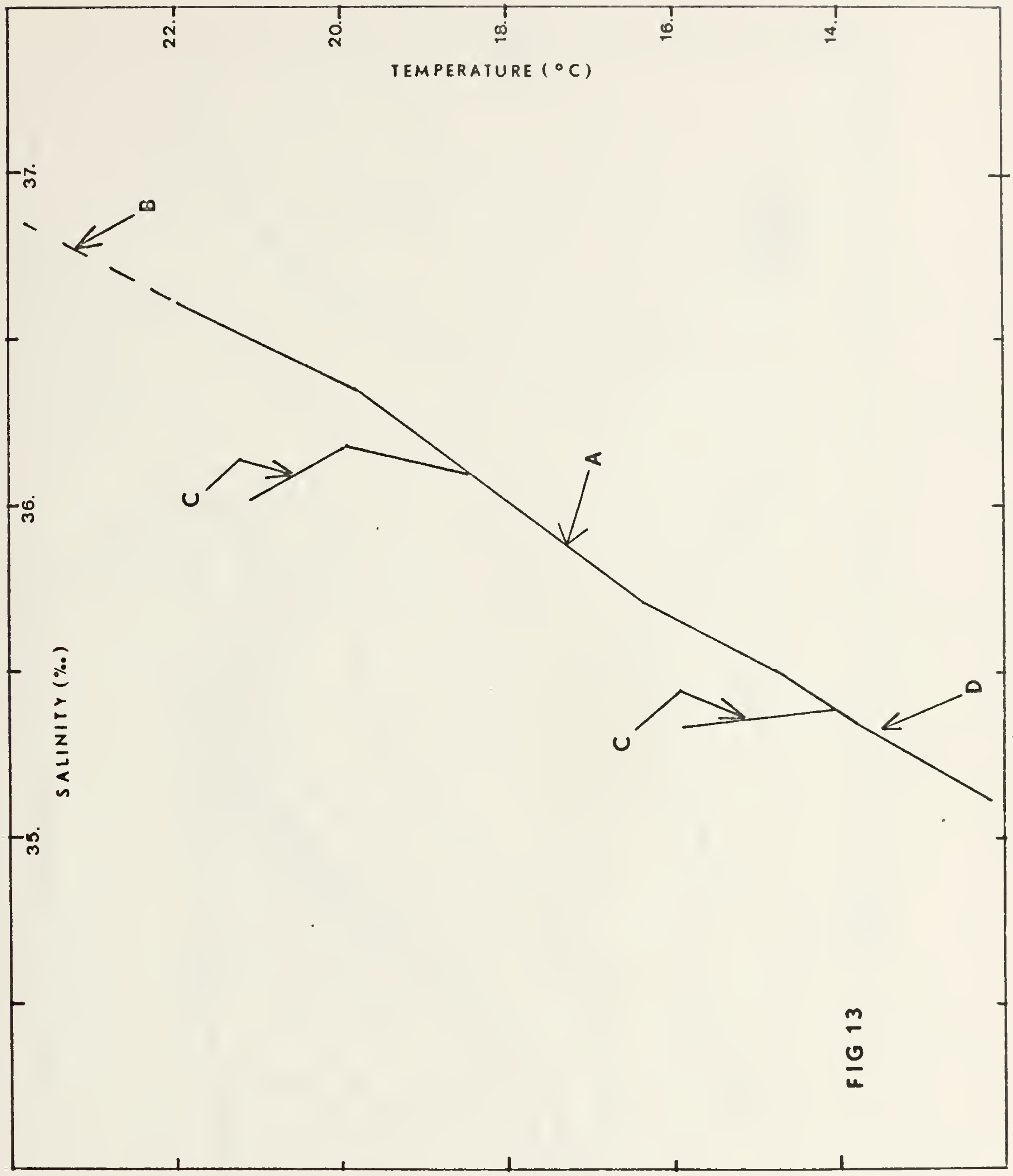
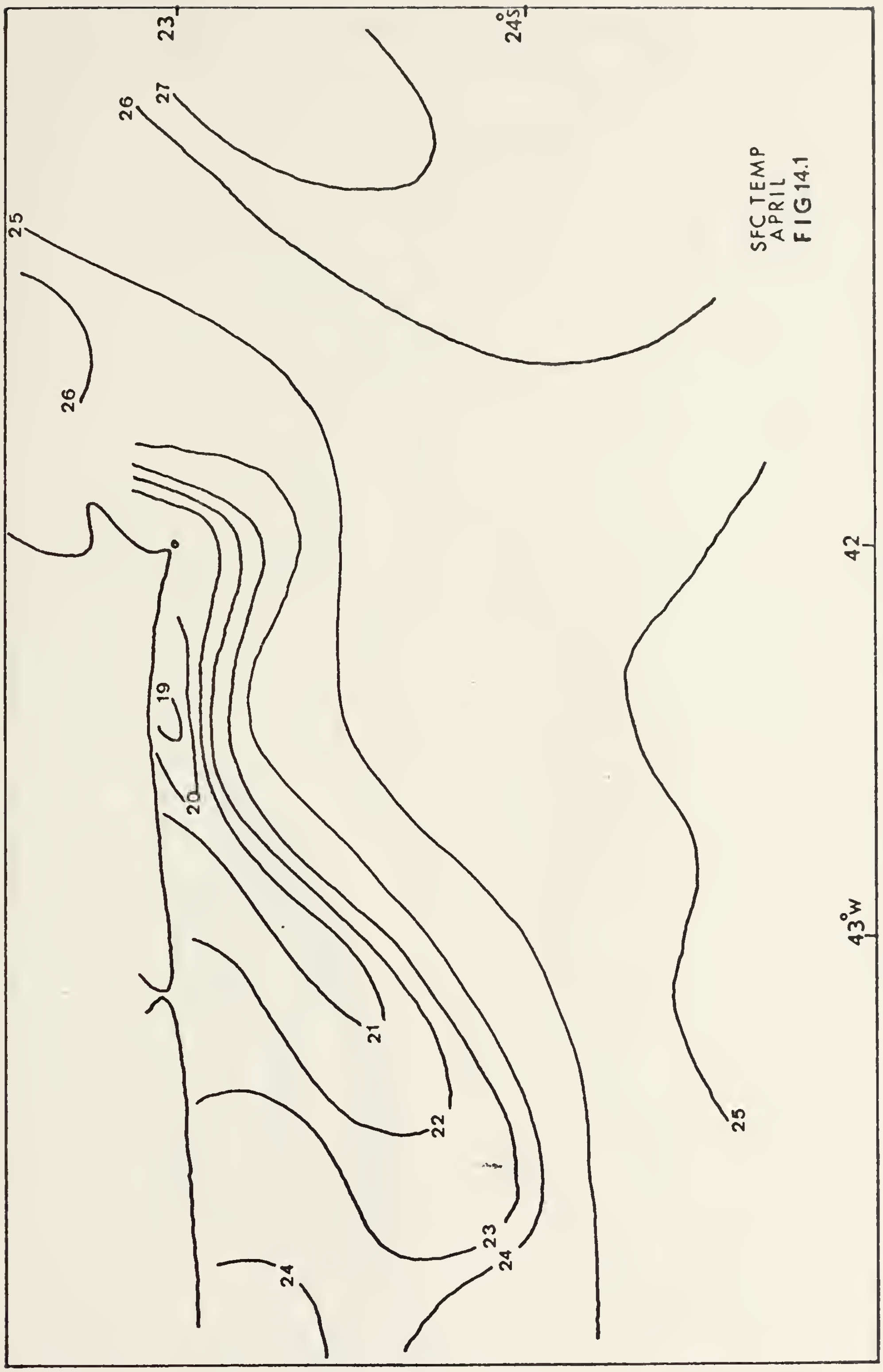
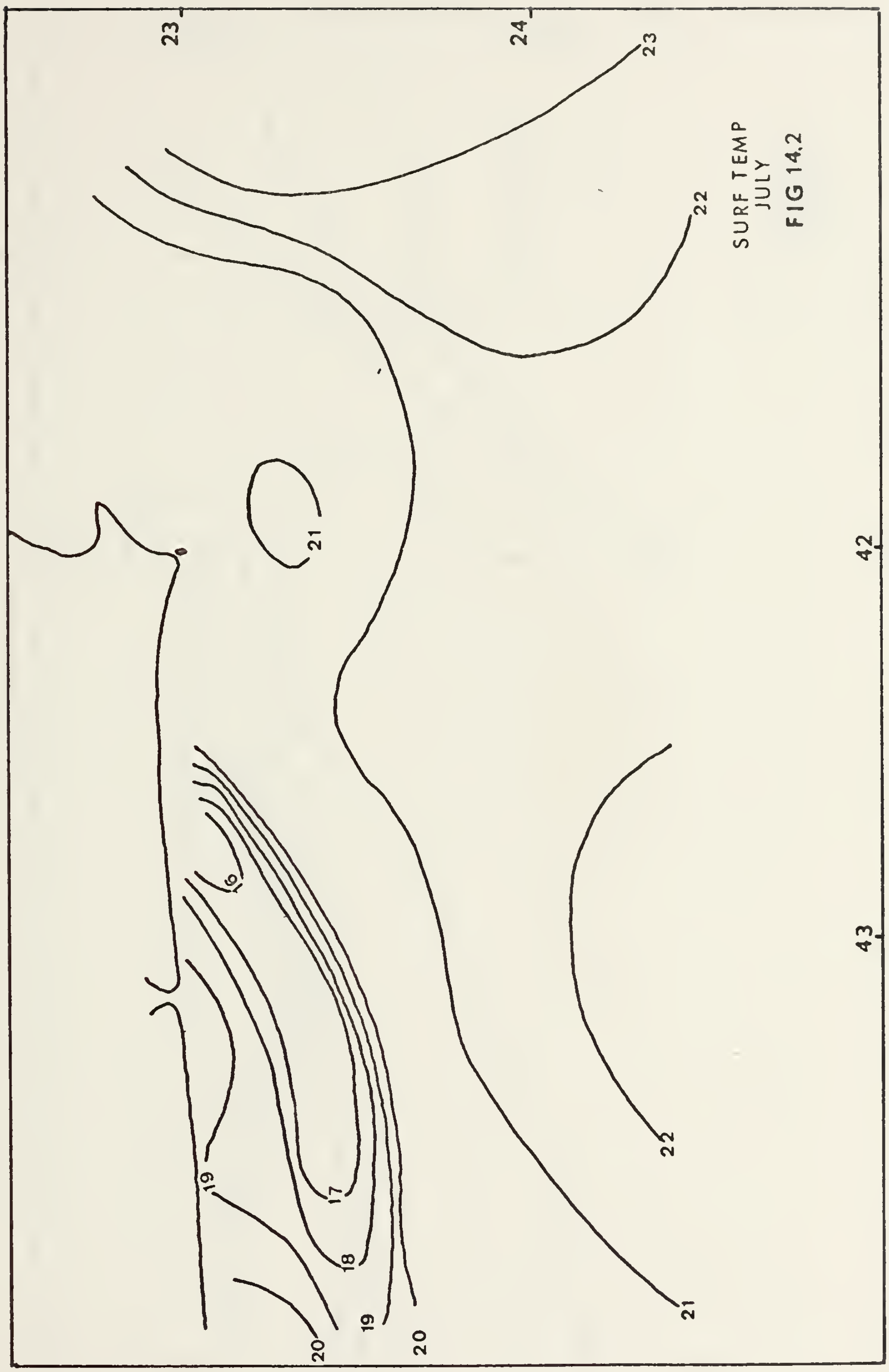


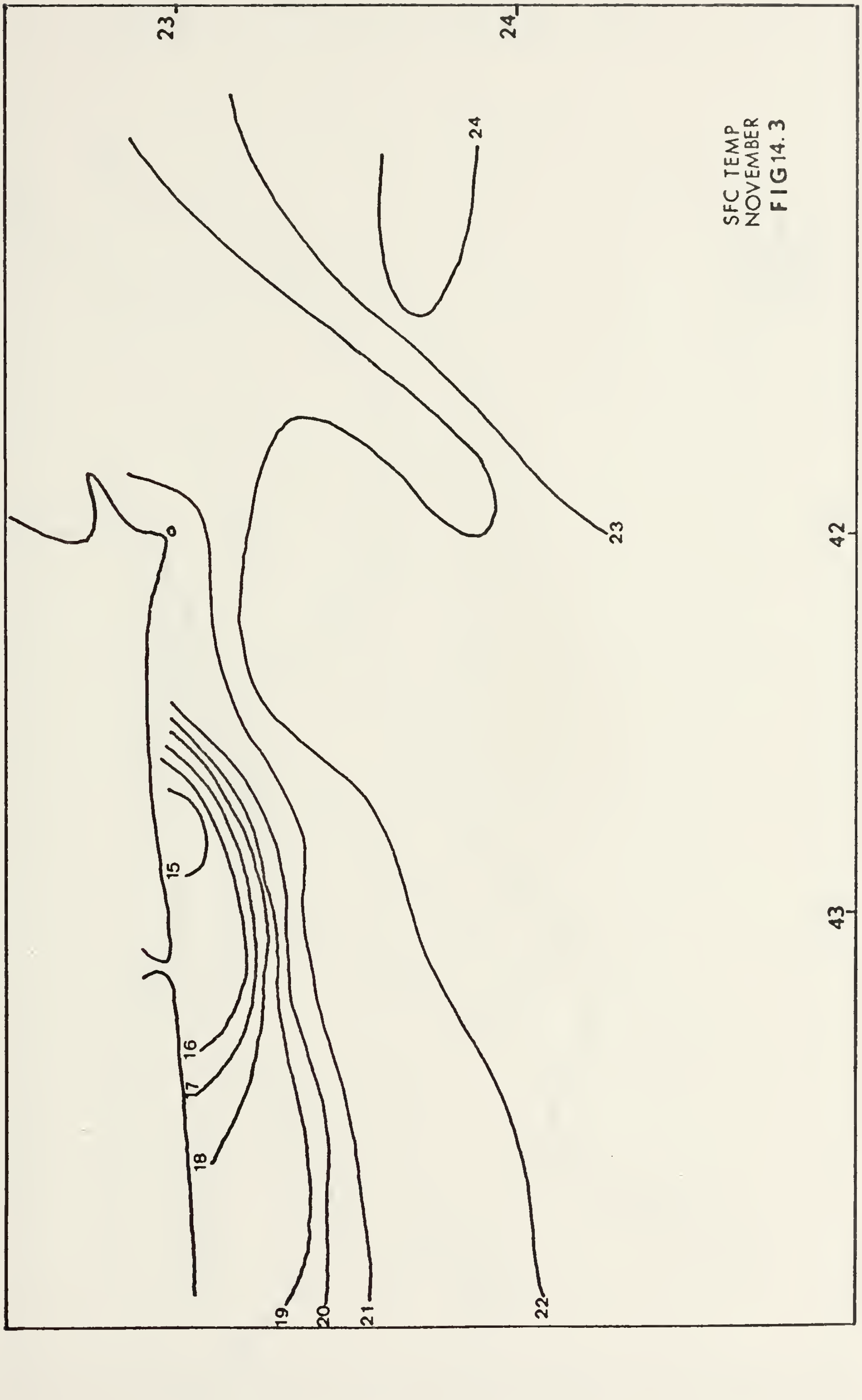
FIG 13



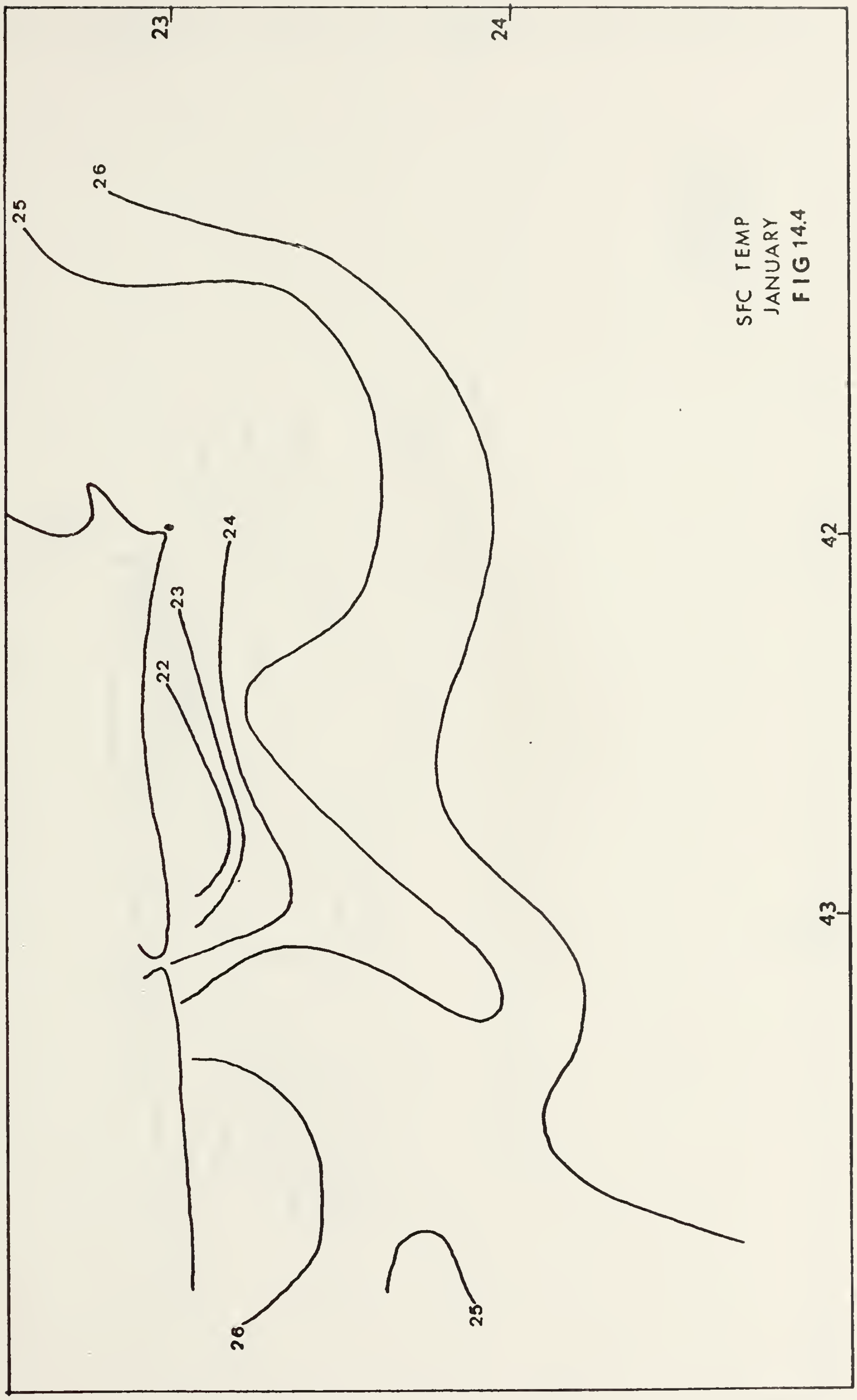
SFC TEMP
APRIL
FIG 14.1



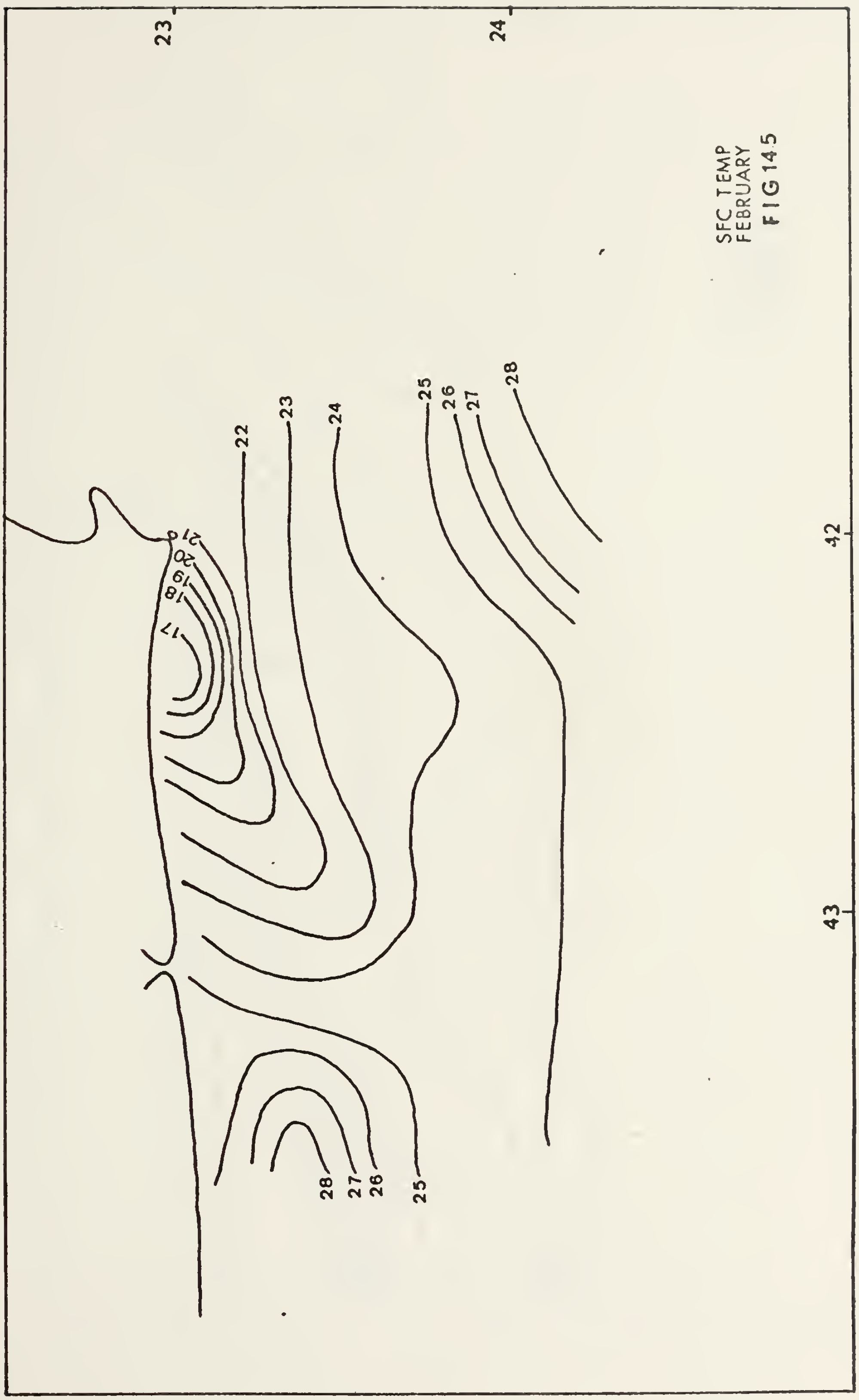
SURF TEMP
JULY
FIG 14.2



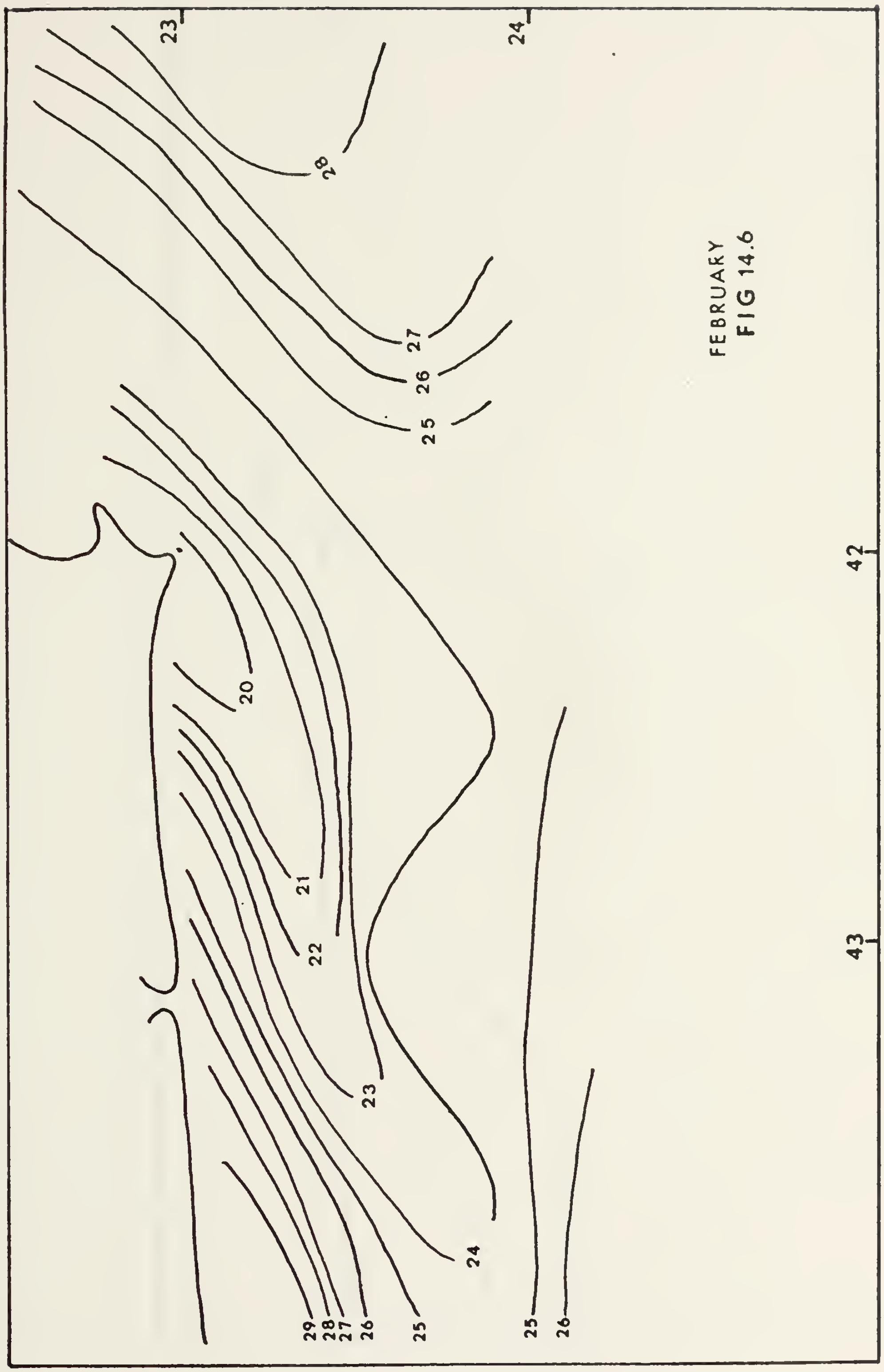
SFC TEMP
NOVEMBER
FIG14.3



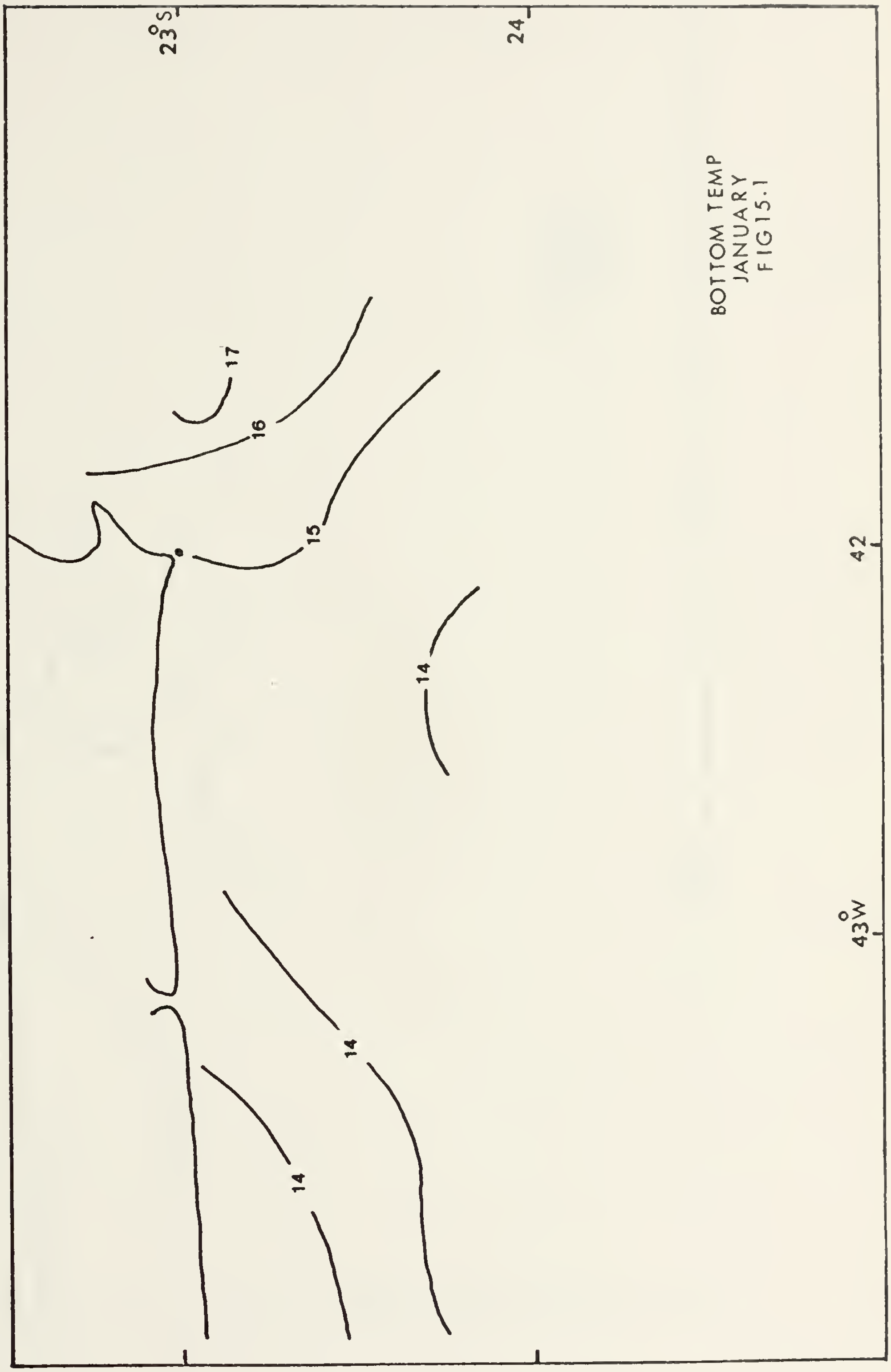
SFC TEMP
JANUARY
FIG 14.4



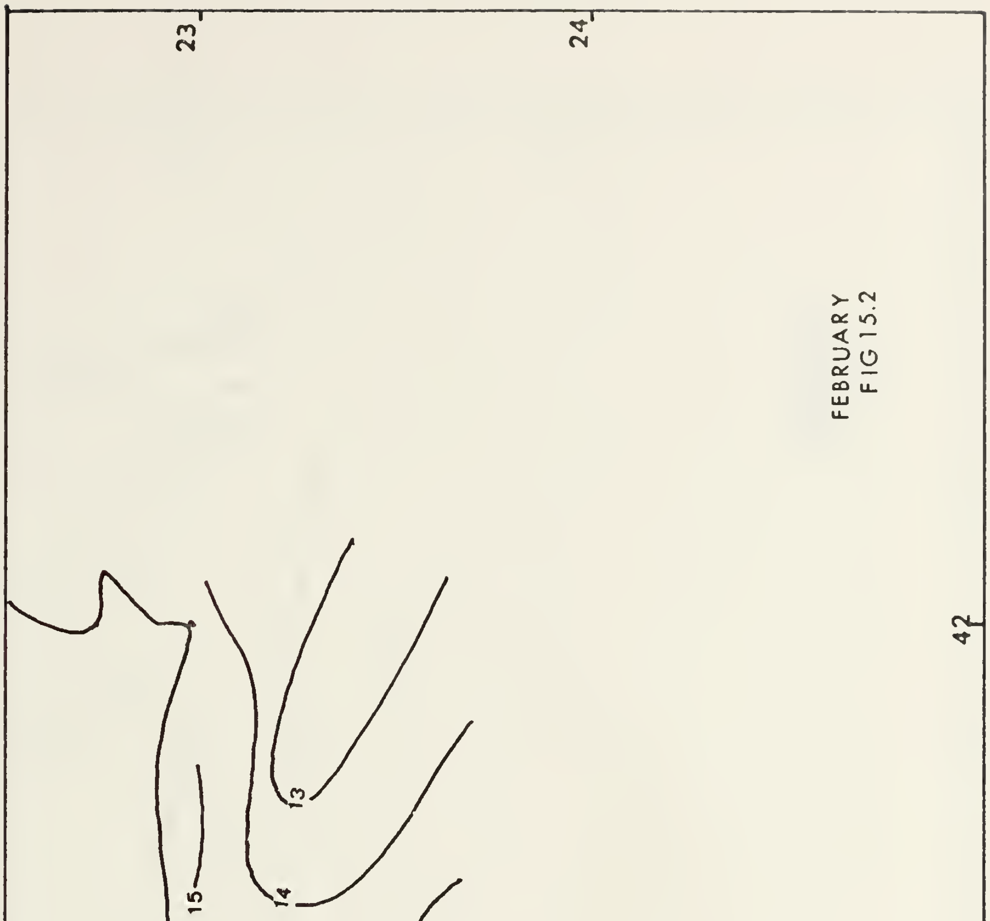
SFC TEMP
FEBRUARY
FIG 14.5



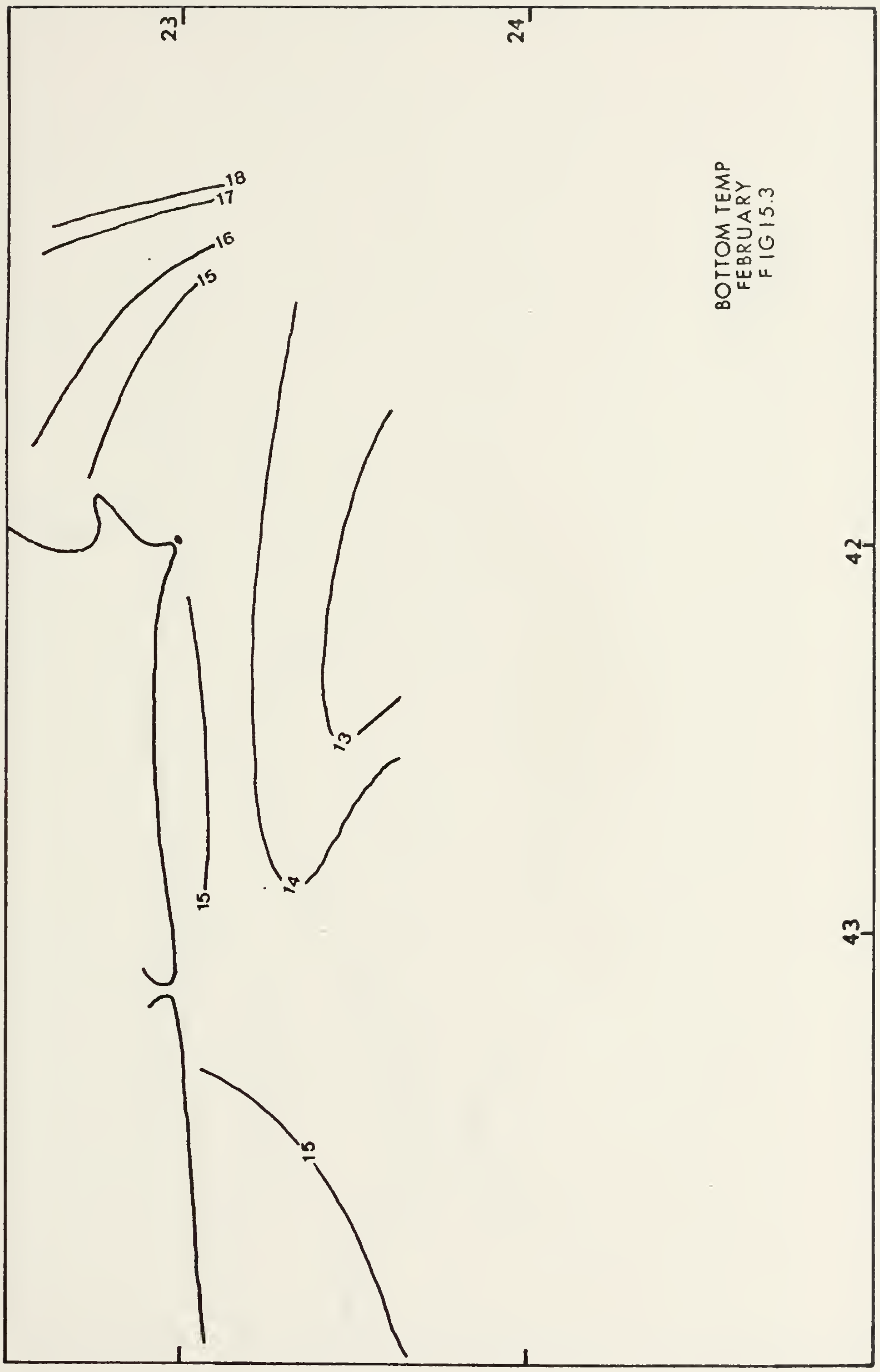
FEBRUARY
FIG 14.6



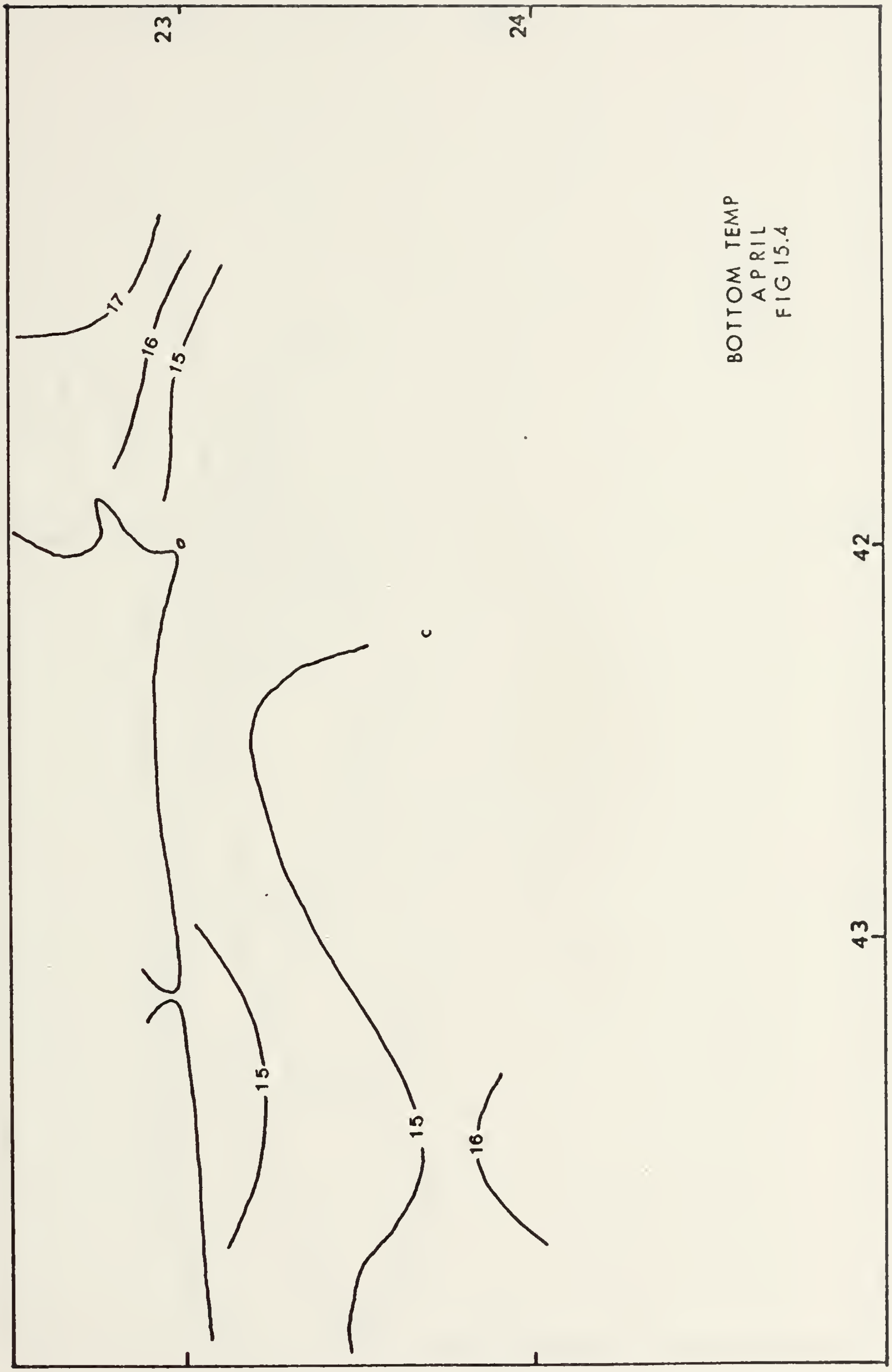
BOTTOM TEMP
JANUARY
FIG15.1



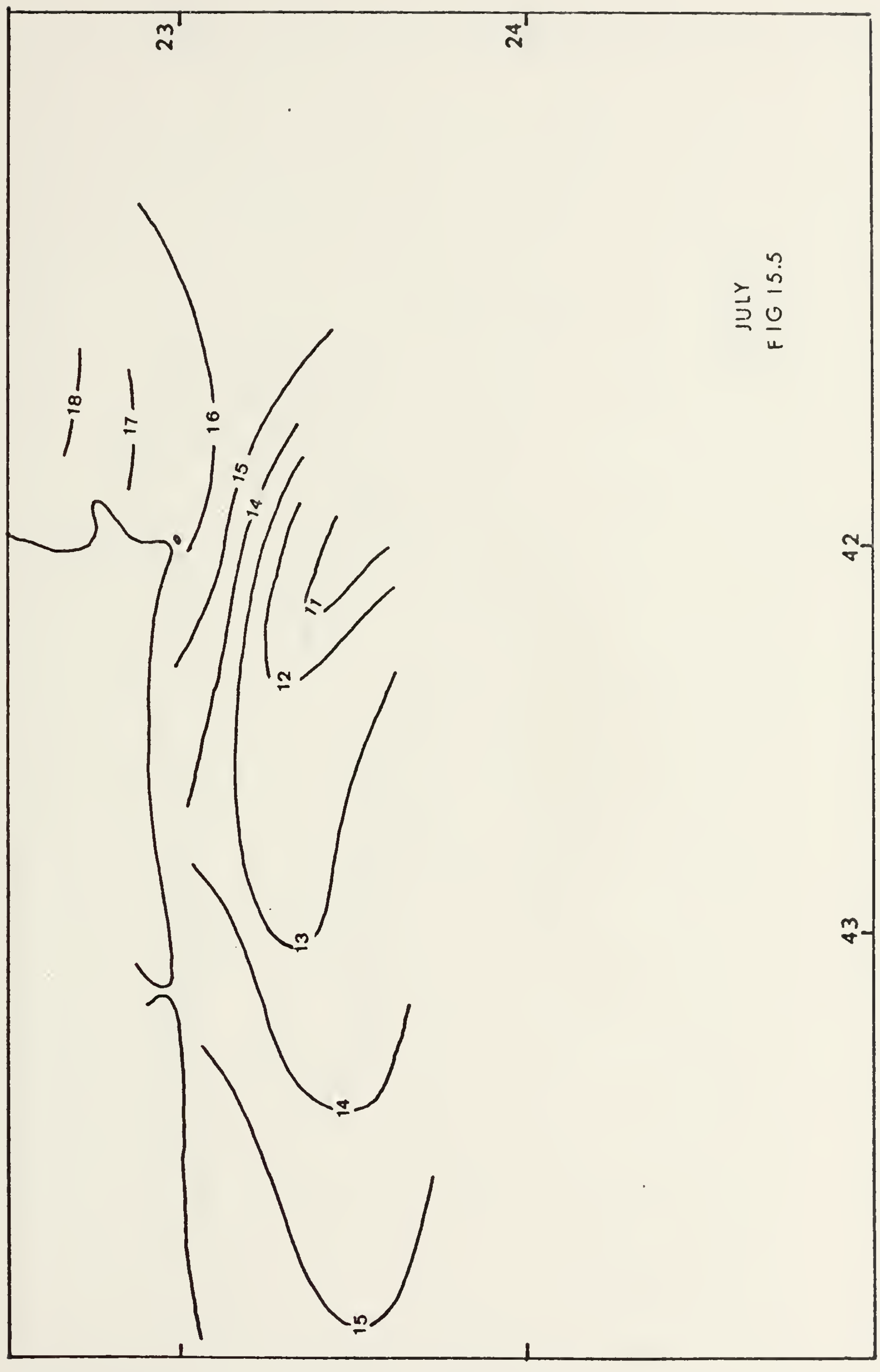
FEBRUARY
FIG 15.2



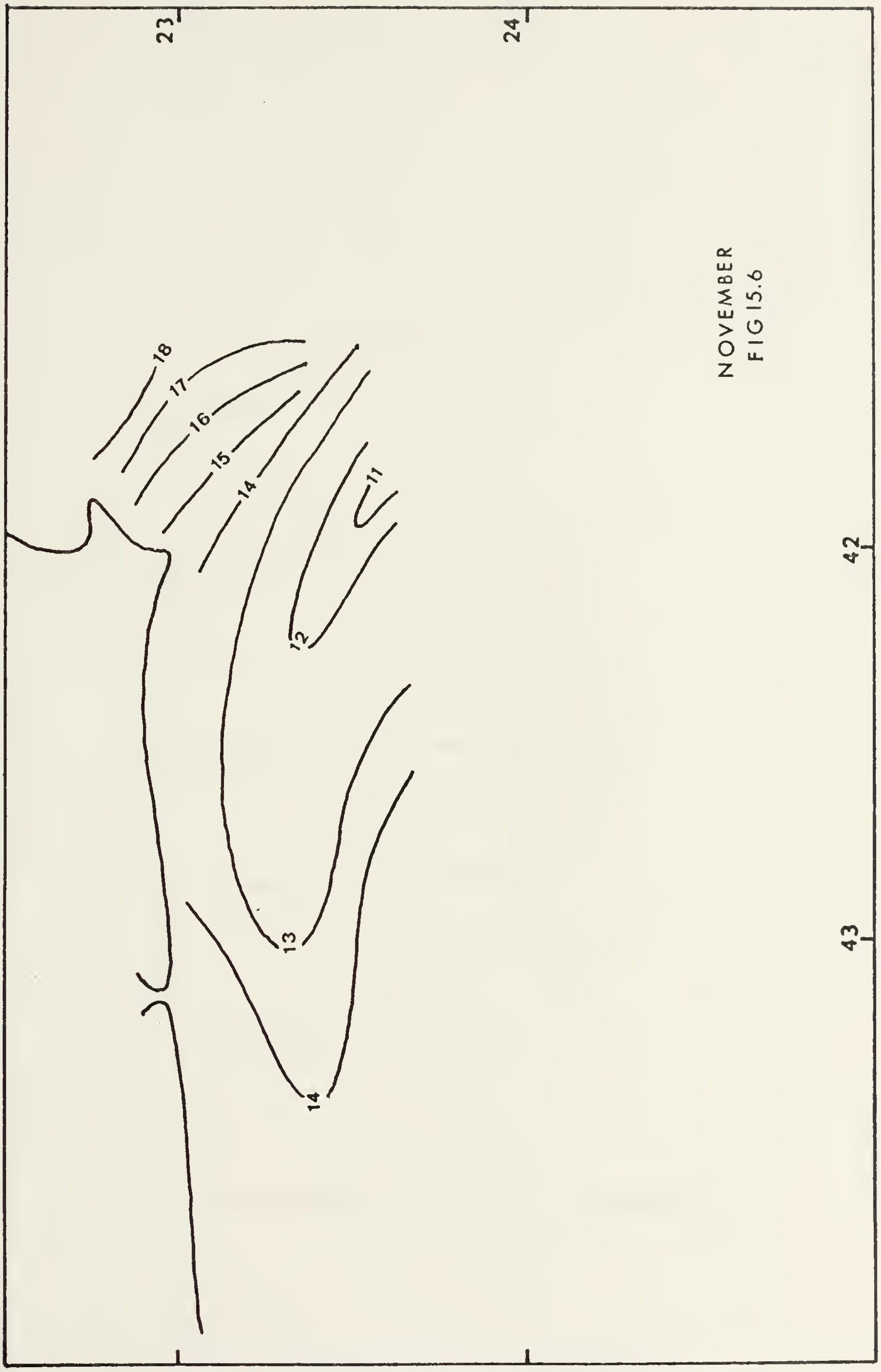
BOTTOM TEMP
FEBRUARY
FIG 15.3



BOTTOM TEMP
APRIL
FIG 15.4



JULY
FIG 15.5



NOVEMBER
FIG 15.6

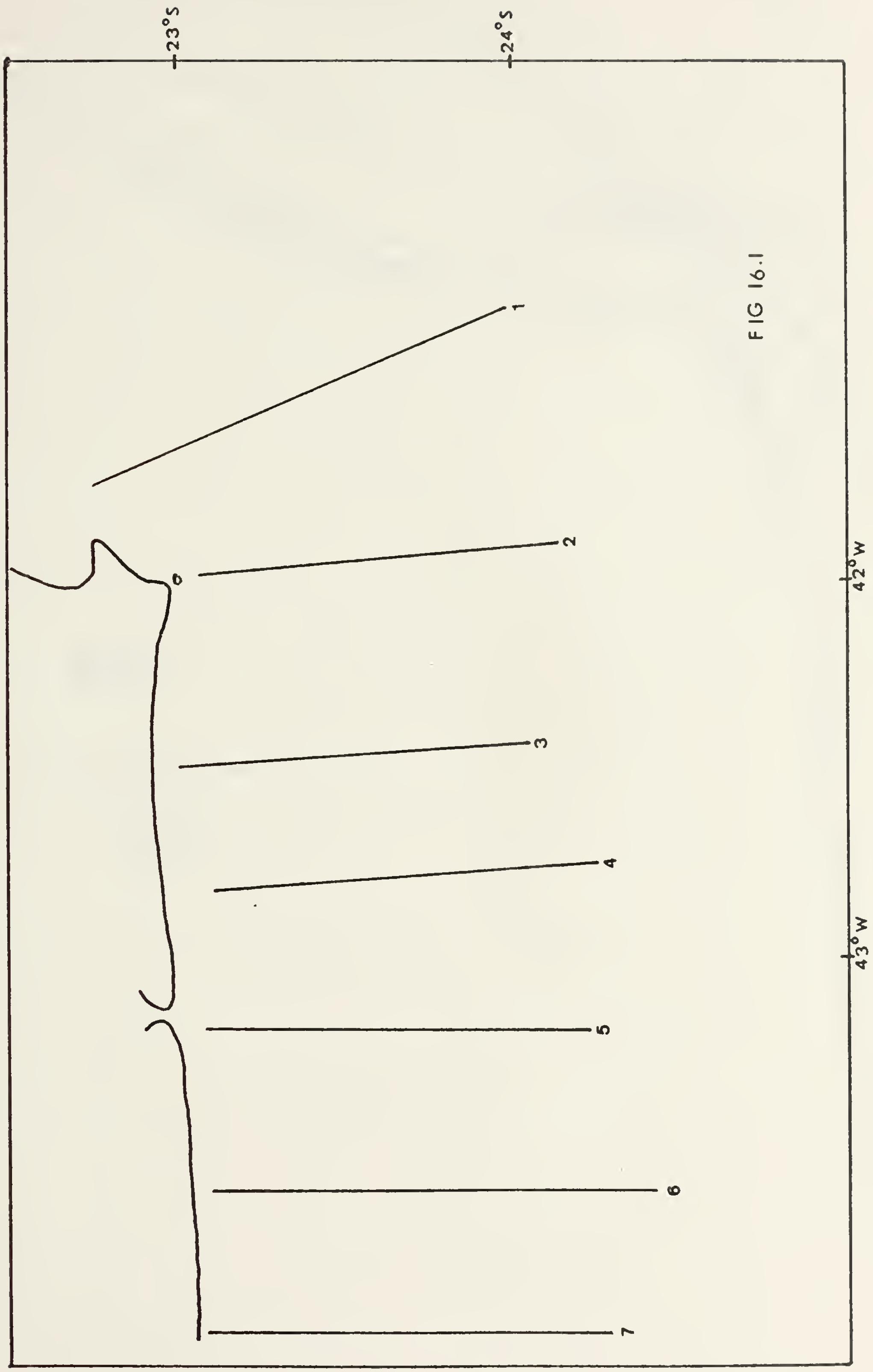


FIG 16.1

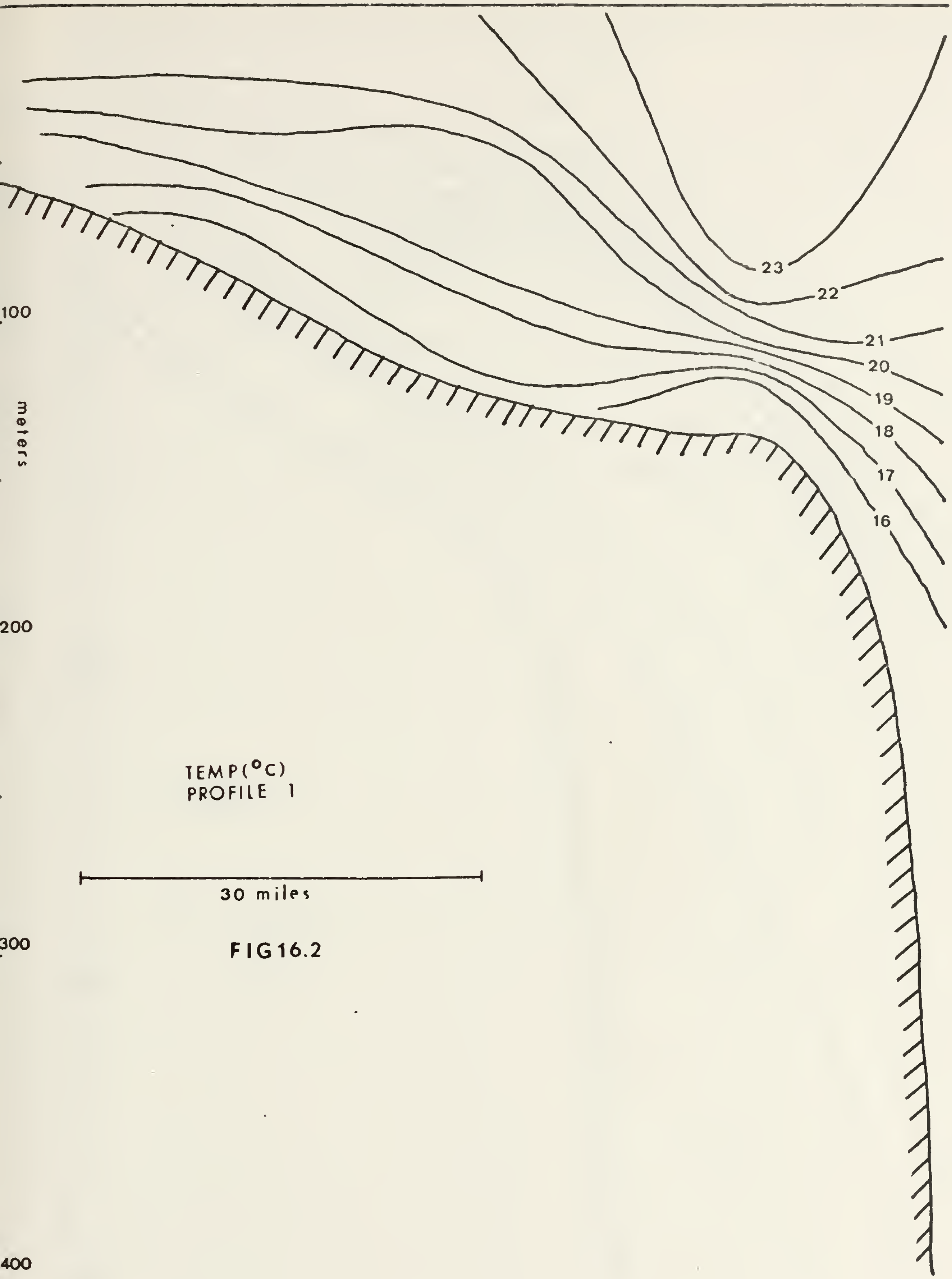
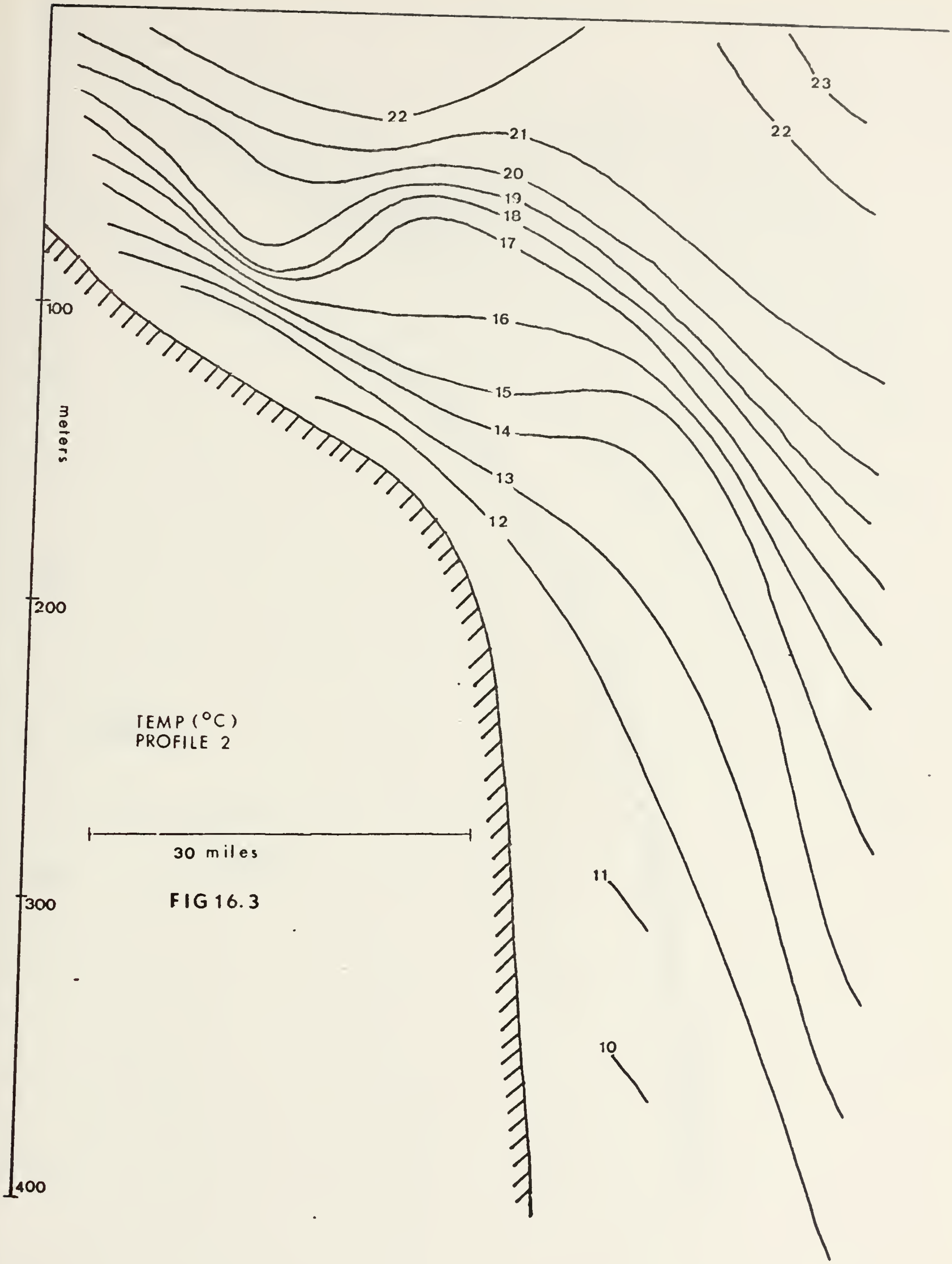

100
200
300
400
meters
23
22
21
20
19
18
17
16
TEMP(°C)
PROFILE 1
30 miles

FIG16.2



23
22
22
21
20
19
18
17
16
15
14
13
12
11
10
100
200
300
400
meters
TEMP (°C)
PROFILE 2
30 miles

FIG 16.3

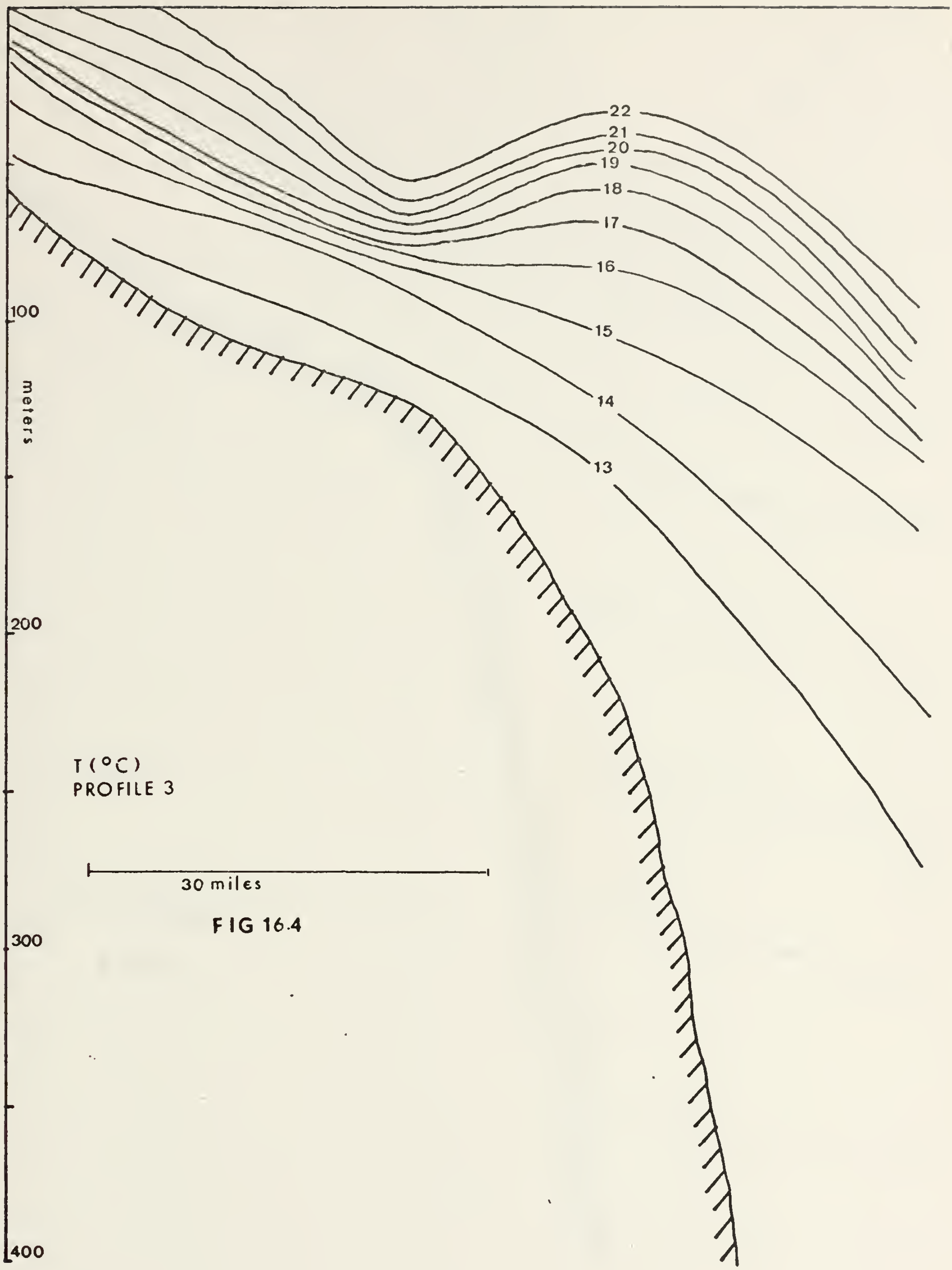
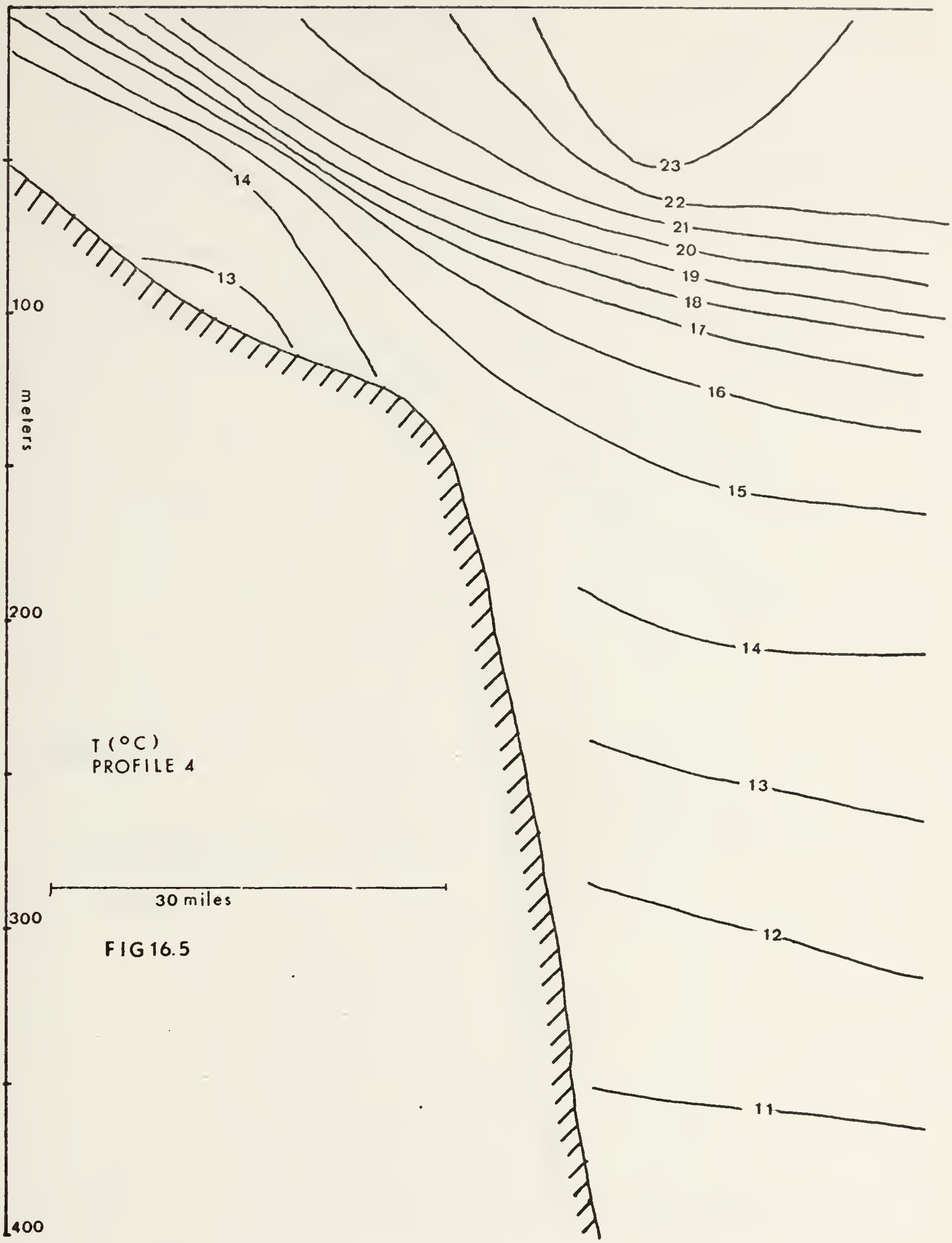
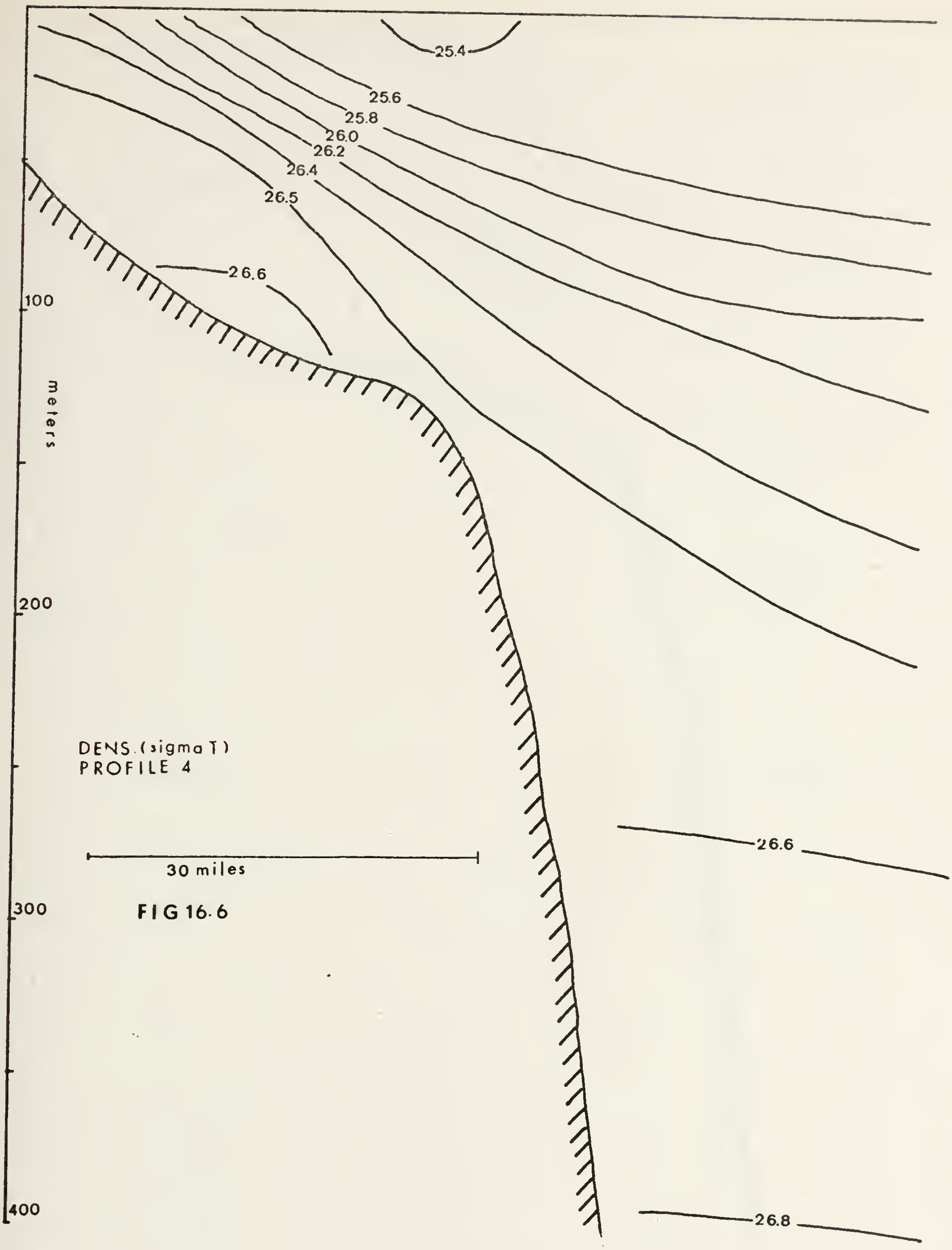

22
21
20
19
18
17
16
15
14
13
100
meters
200
300
400
T (°C)
PROFILE 3
30 miles

FIG 16.4


23
22
21
20
19
18
17
16
15
14
13
12
11
14
13
100
200
300
400
meters
T (°C)
PROFILE 4
30 miles
FIG 16.5



25.4
25.6
25.8
26.0
26.2
26.4
26.5
26.6
100
200
300
400
meters
DENS.(sigma T)
PROFILE 4
30 miles
26.6
26.8

FIG 16.6

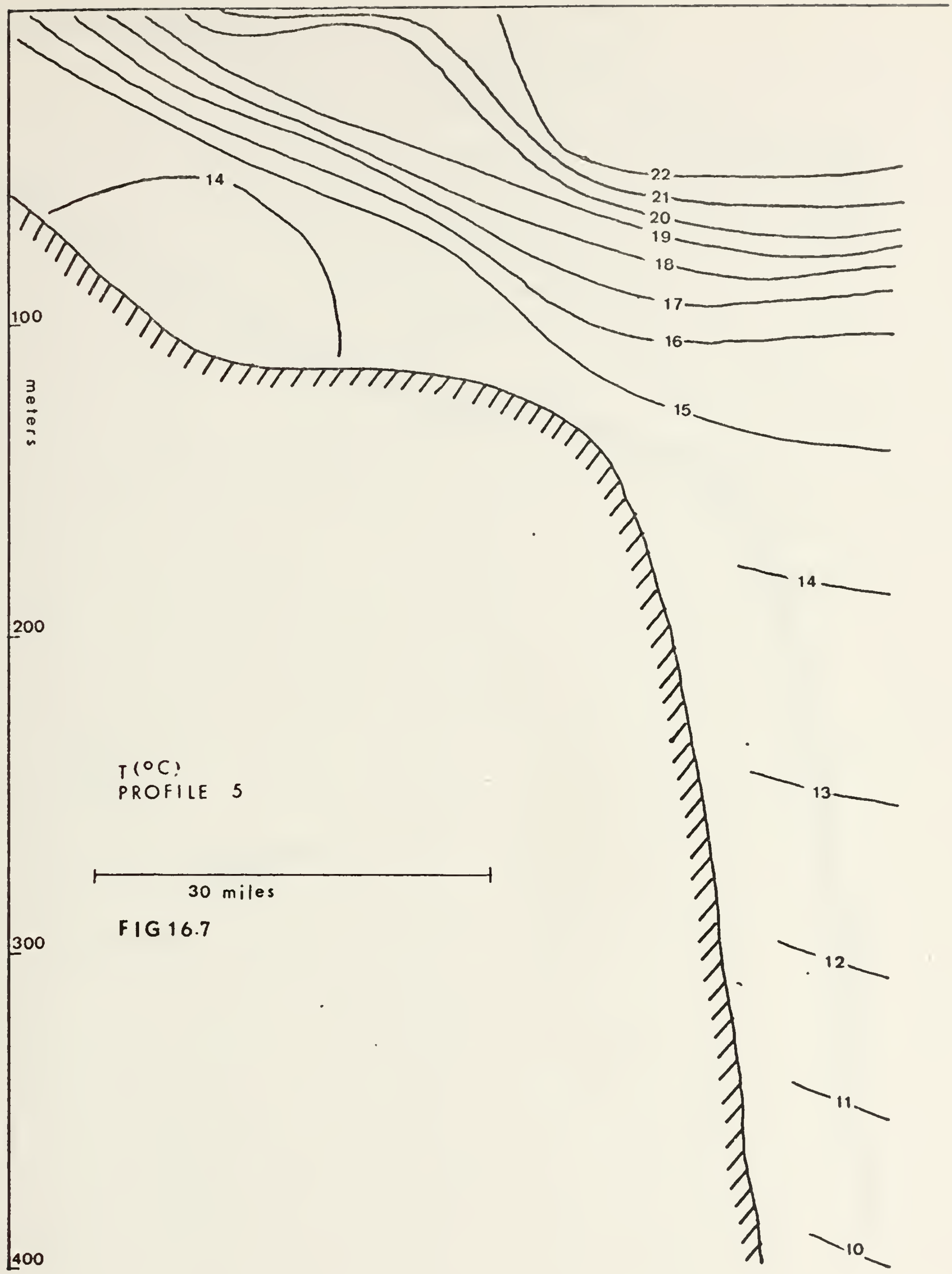
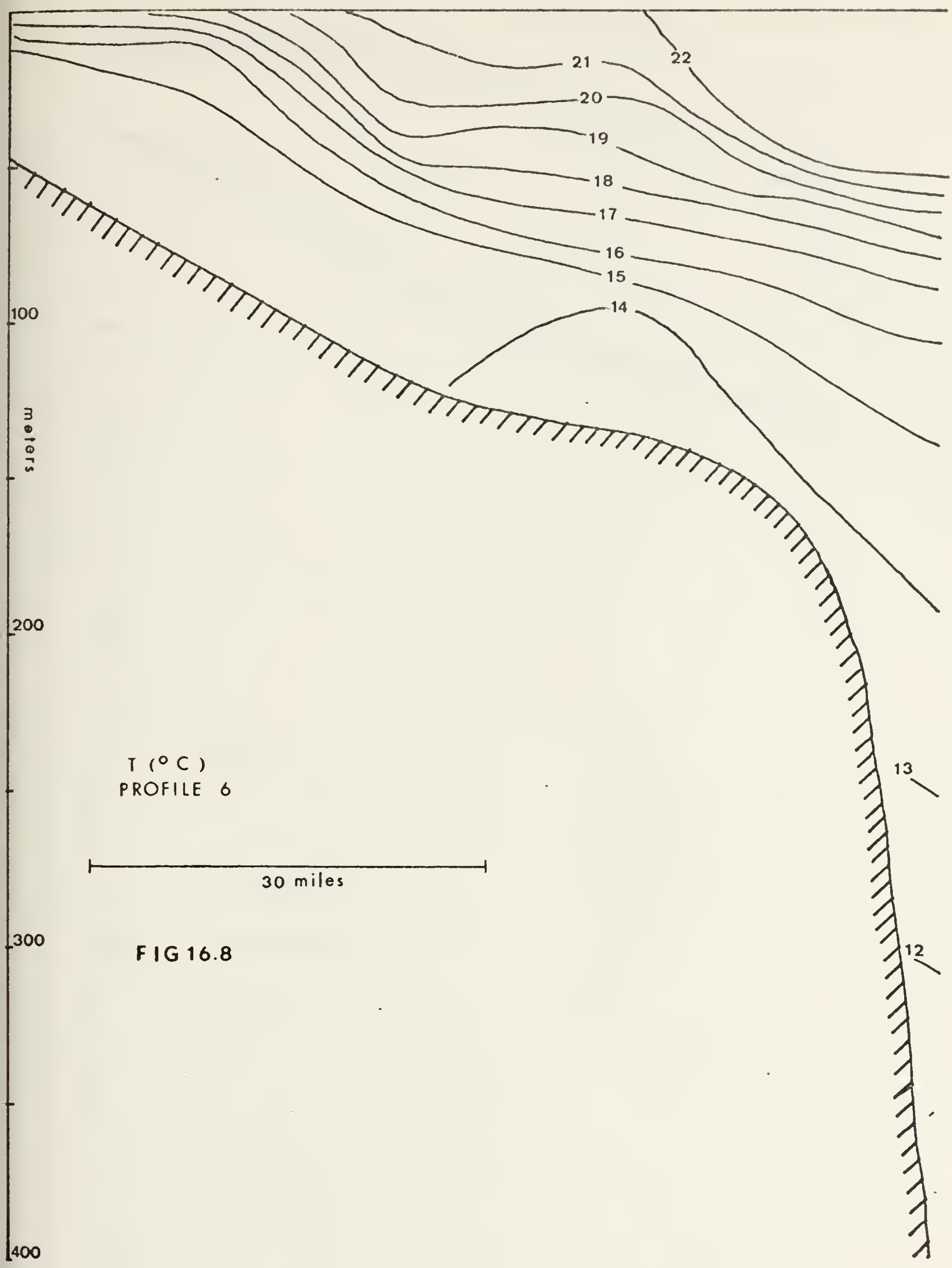

22
21
20
19
18
17
16
15
14
14
13
12
11
10
100
200
300
400
meters
T (°C)
PROFILE 5
30 miles

FIG 16.7



22
21
20
19
18
17
16
15
14
13
12
100
200
300
400
meters
T (°C)
PROFILE 6
30 miles

FIG 16.8

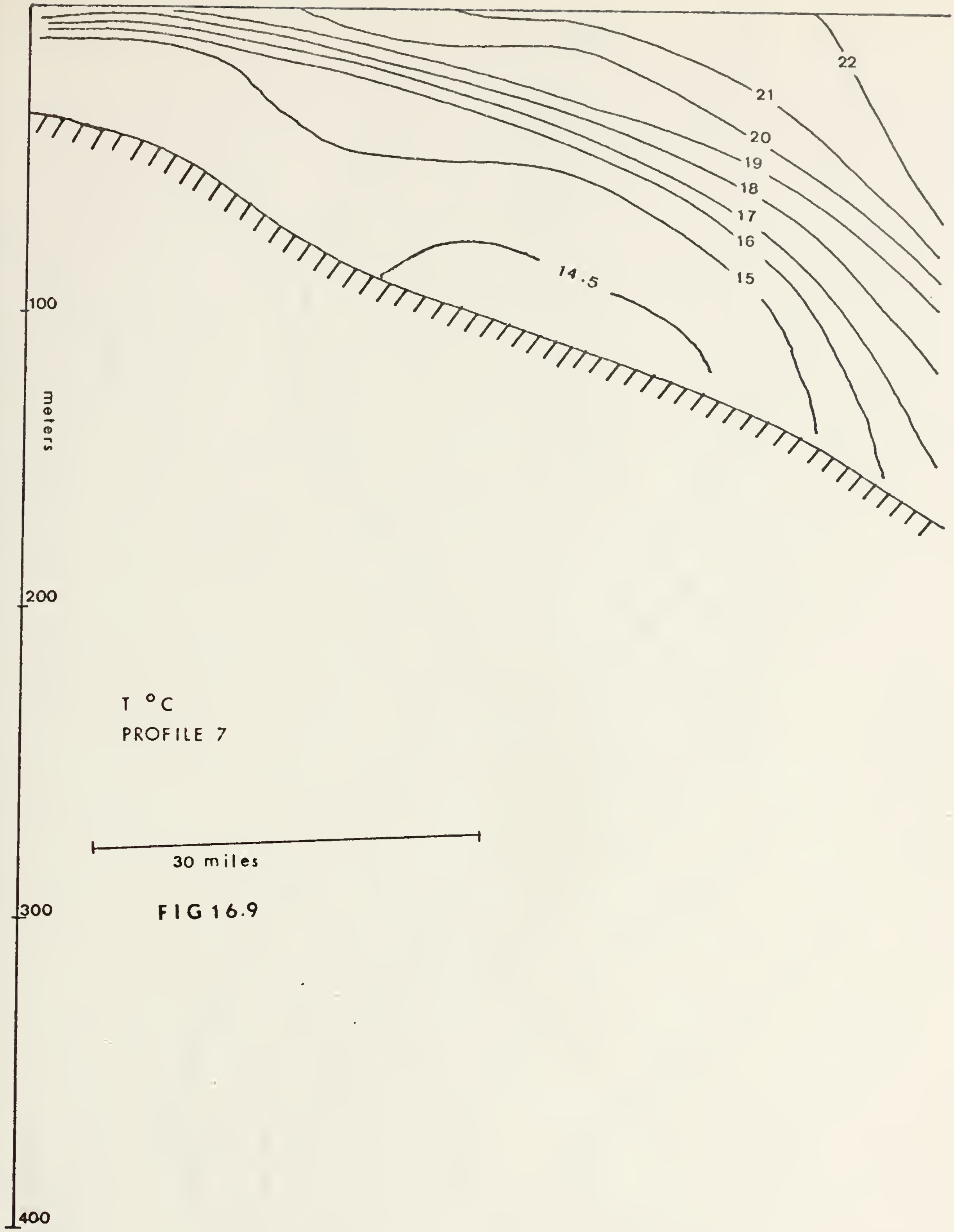

22
21
20
19
18
17
16
15
14.5
100
200
300
400
meters
T °C
PROFILE 7
30 miles

FIG 16.9

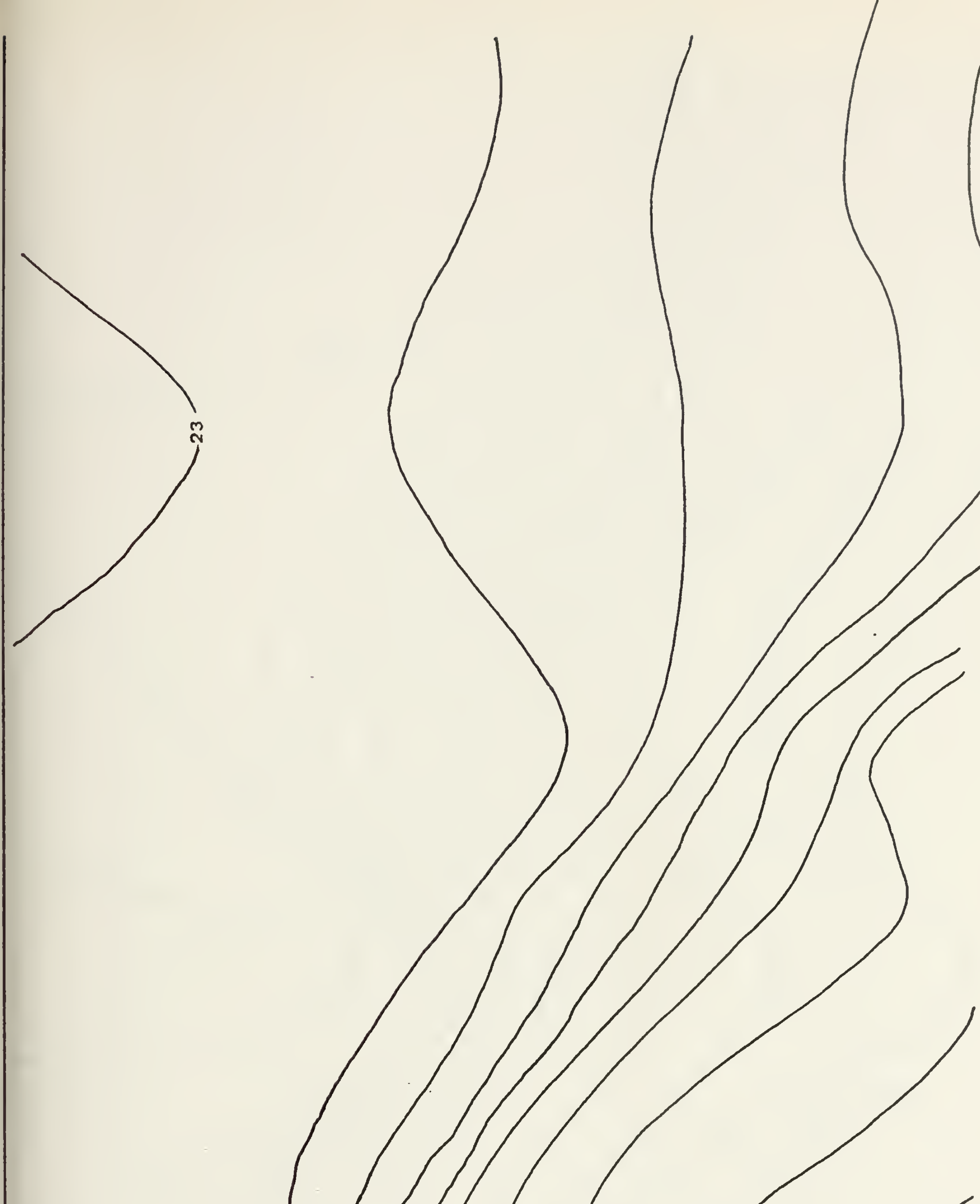
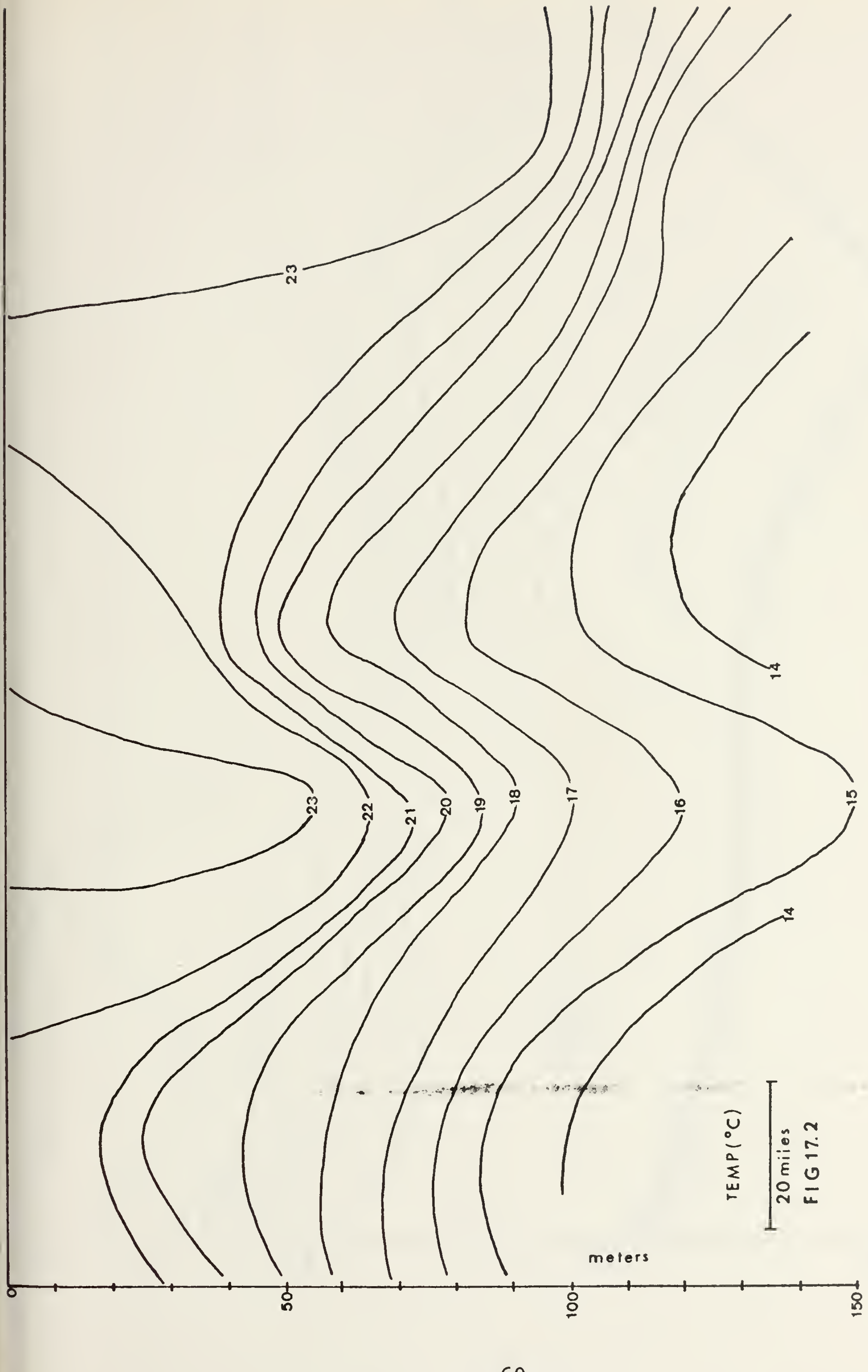


FIG 17.1


23
23
22
21
20
19
18
17
16
15
14
14
meters
0
50
100
150
TEMP (°C)
20 miles
FIG 17.2

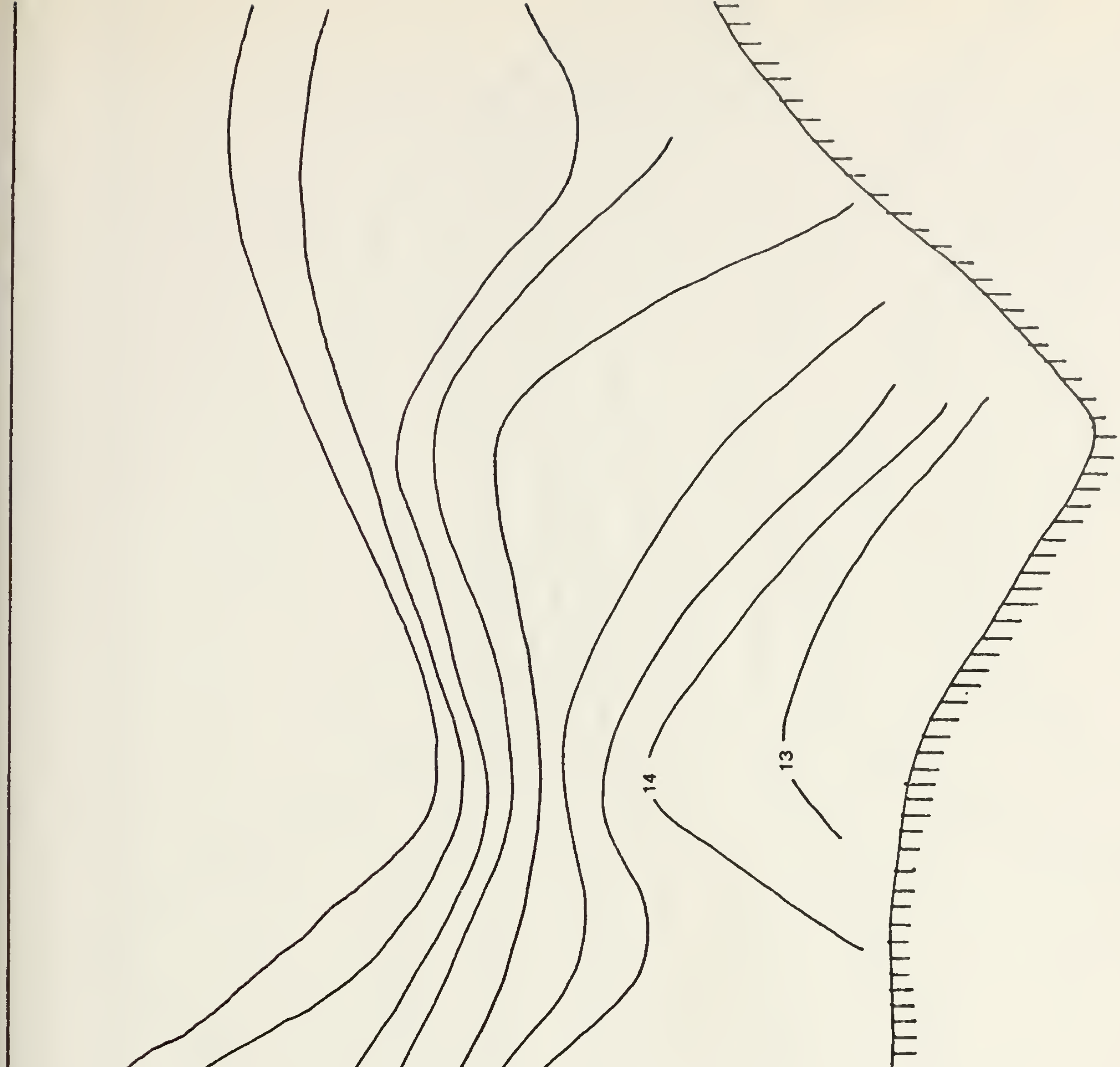


FIG 17.3

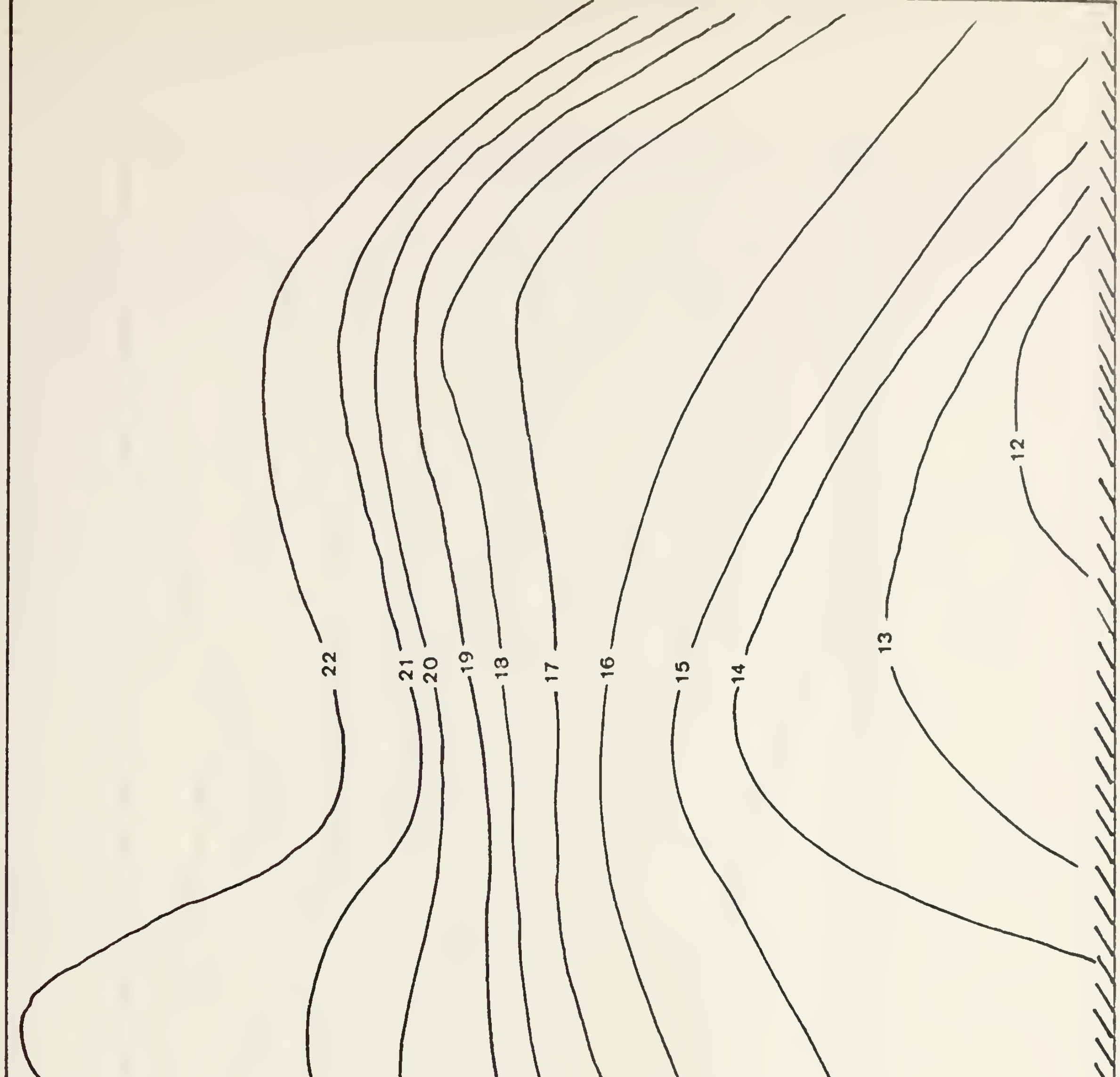


FIG 17.4

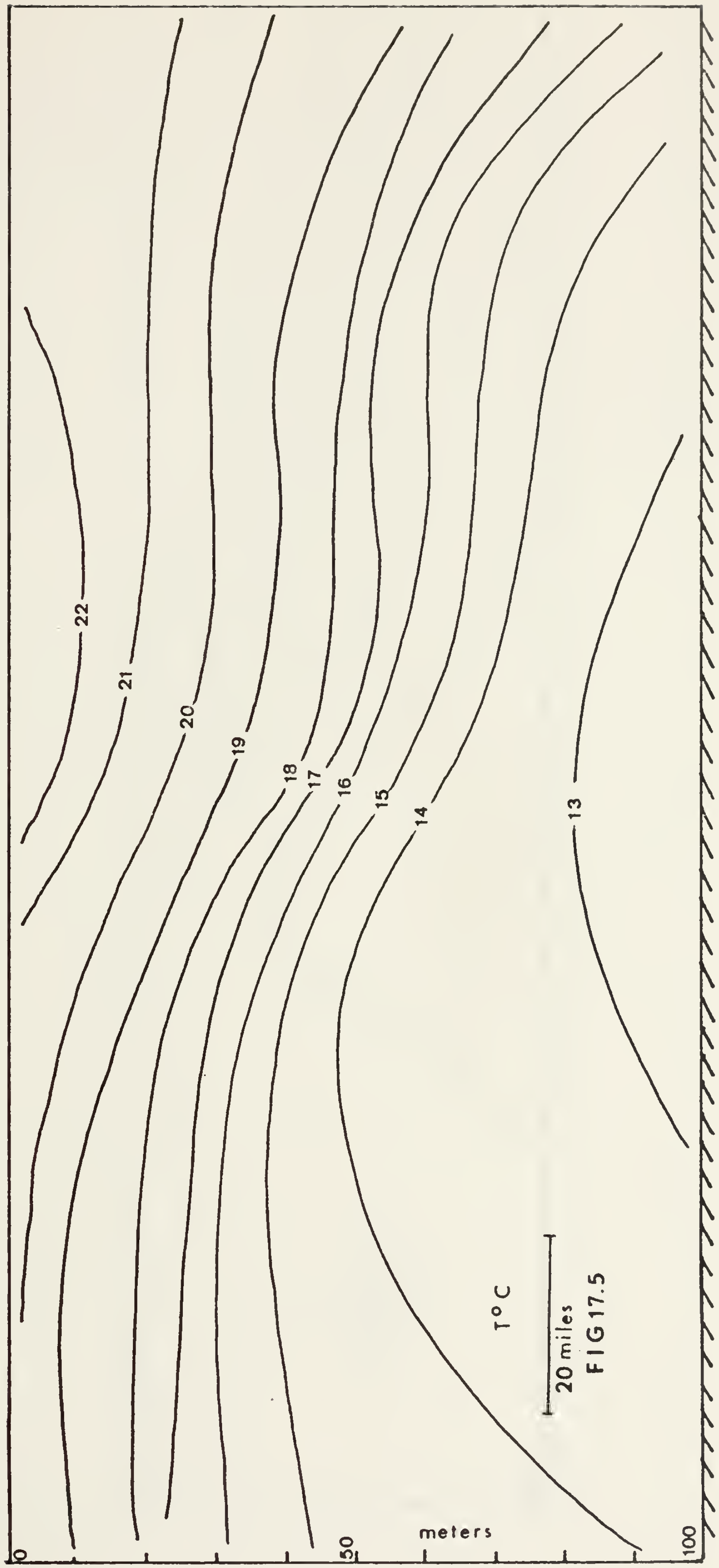


FIG17.5

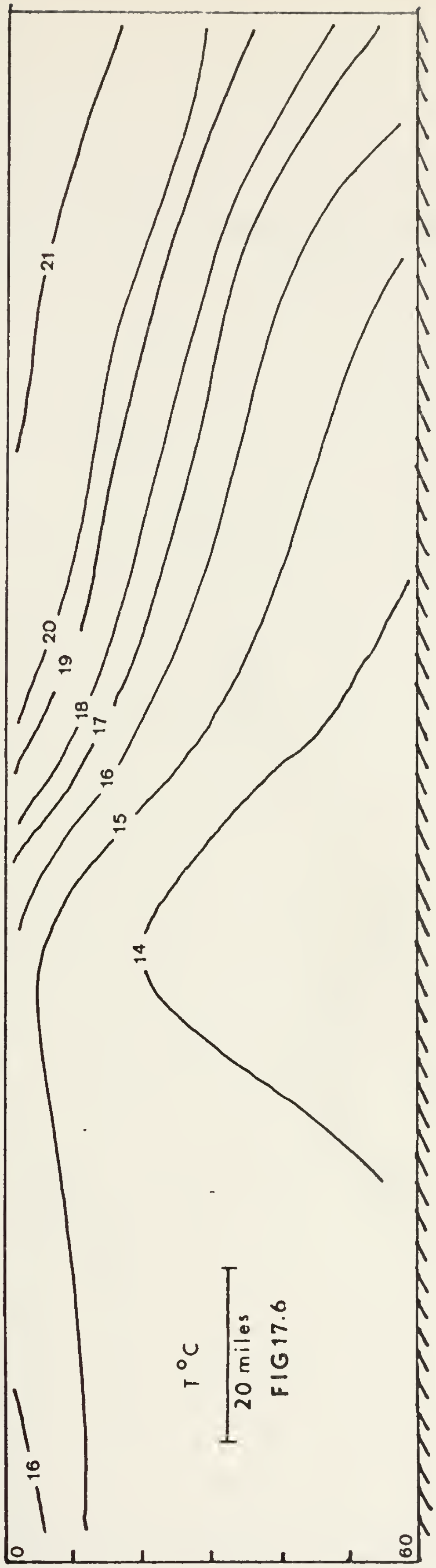
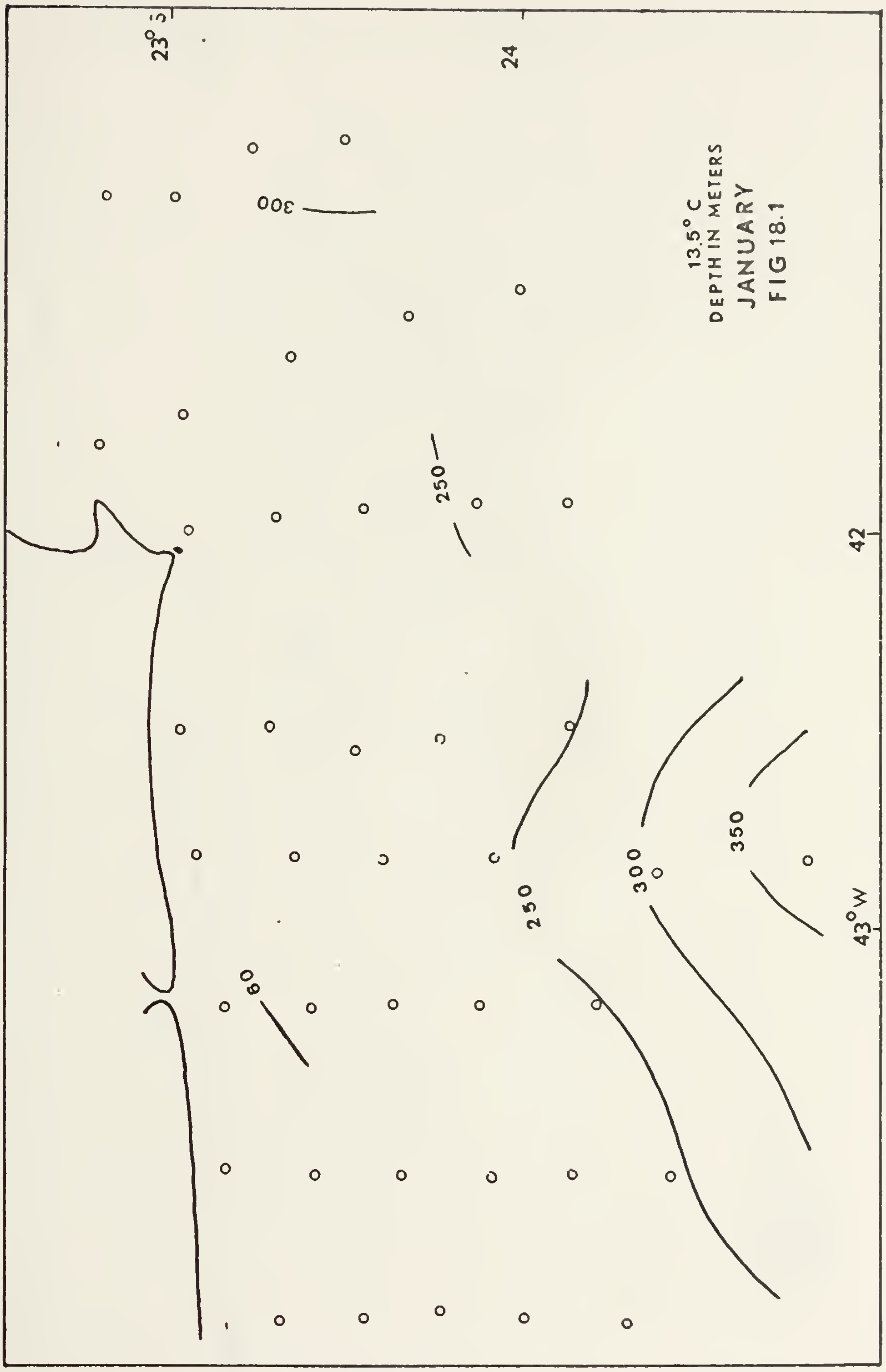
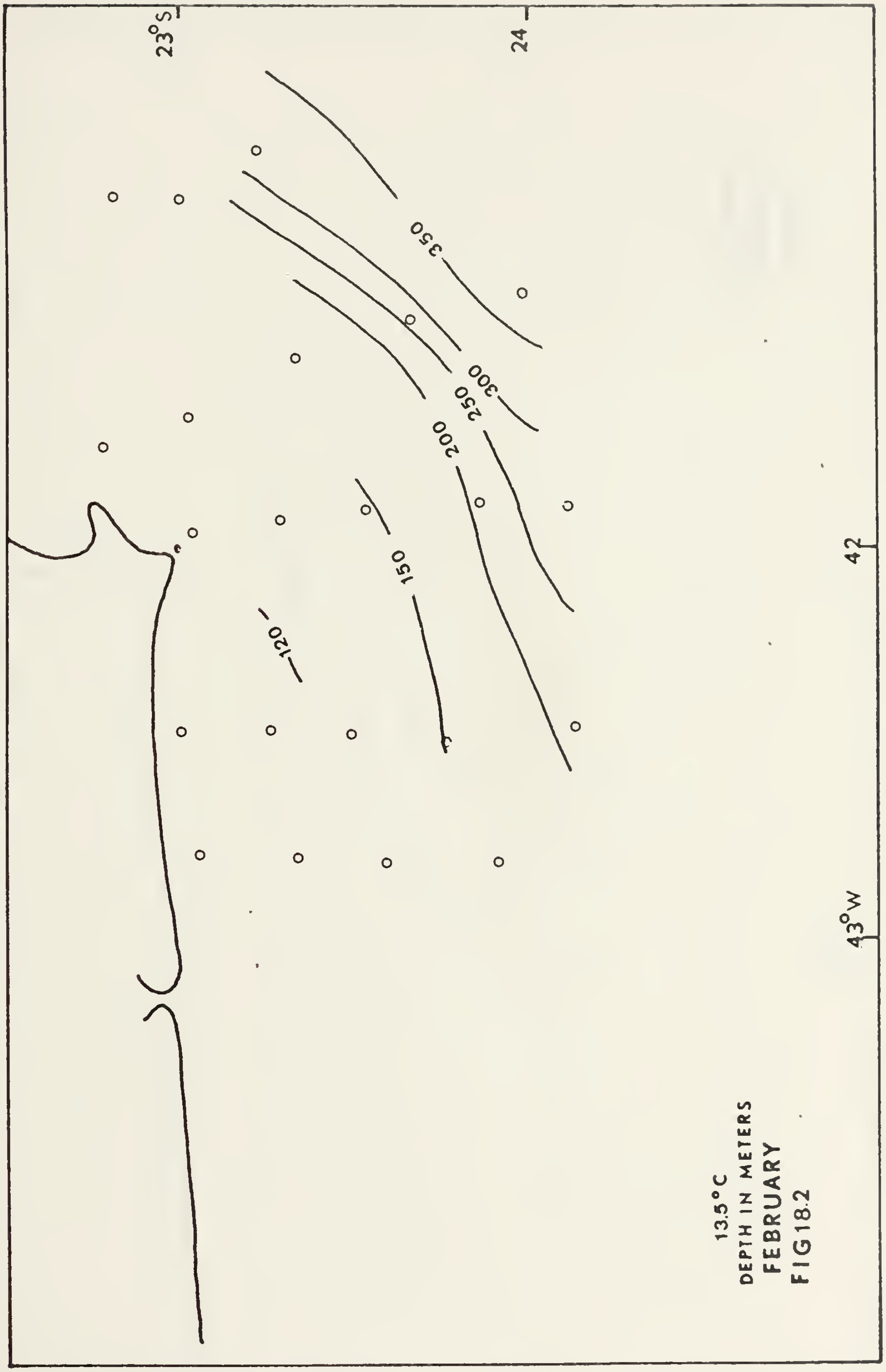


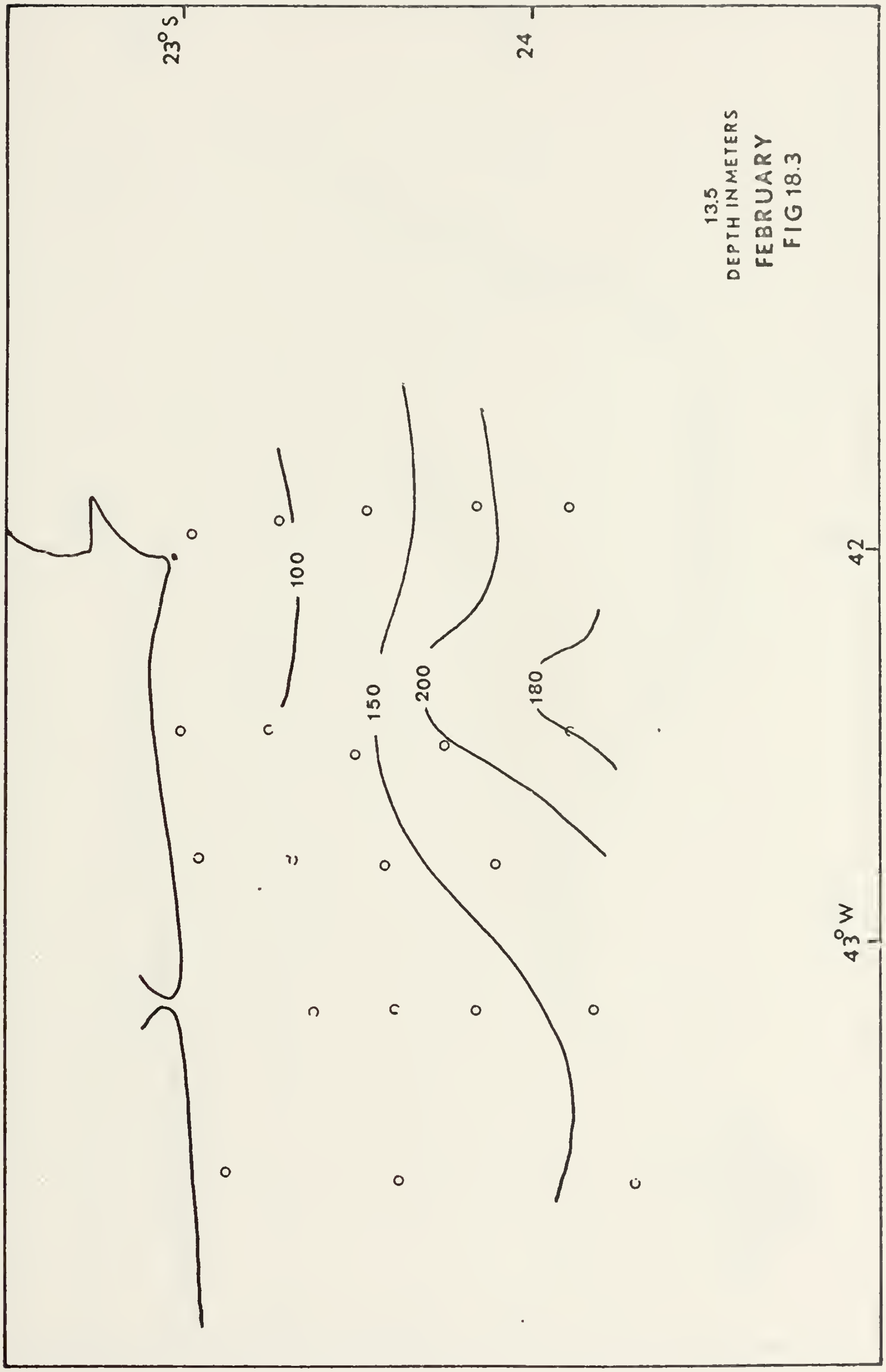
FIG17.6



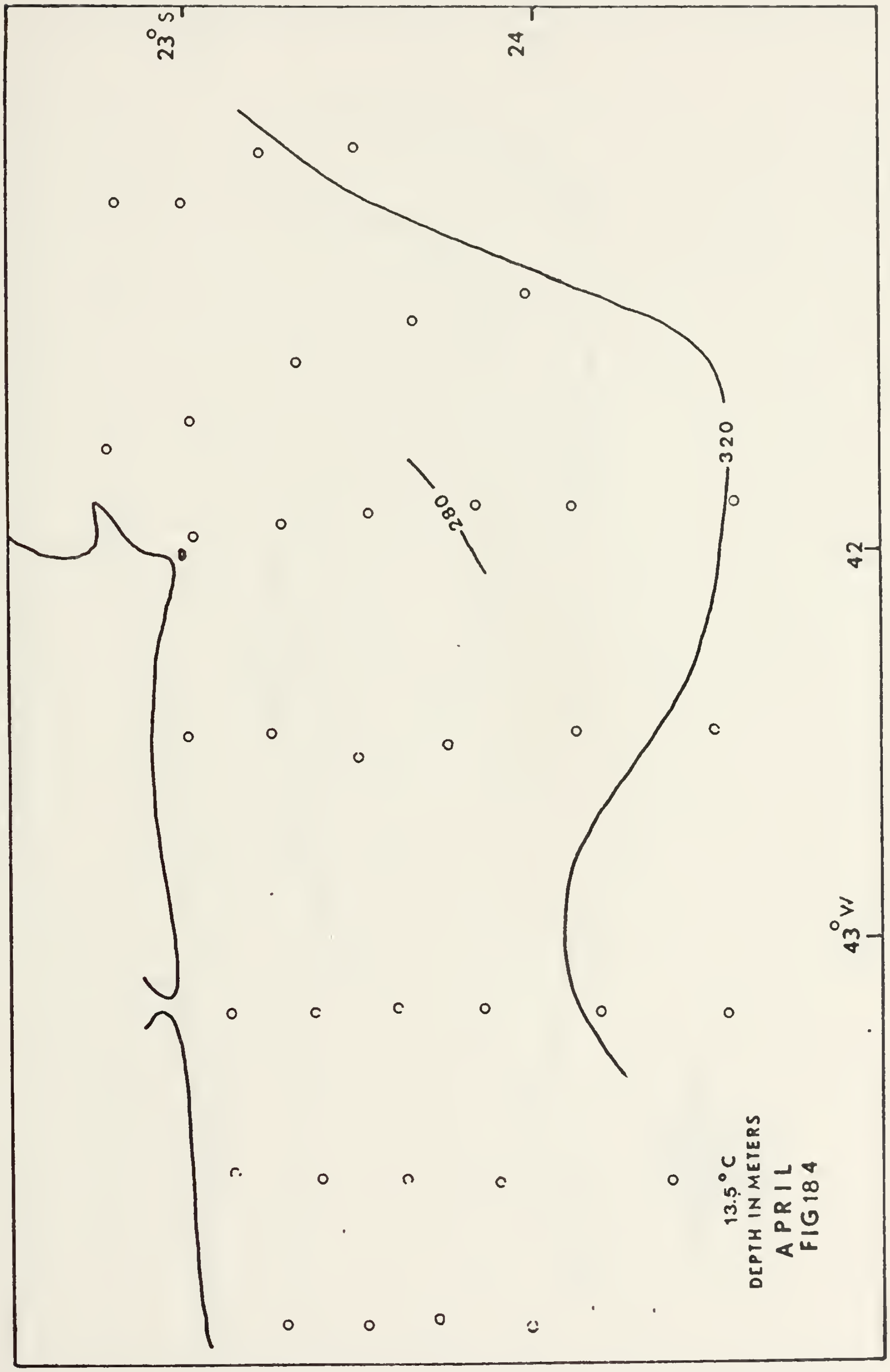
13.5° C
DEPTH IN METERS
JANUARY
FIG 18.1



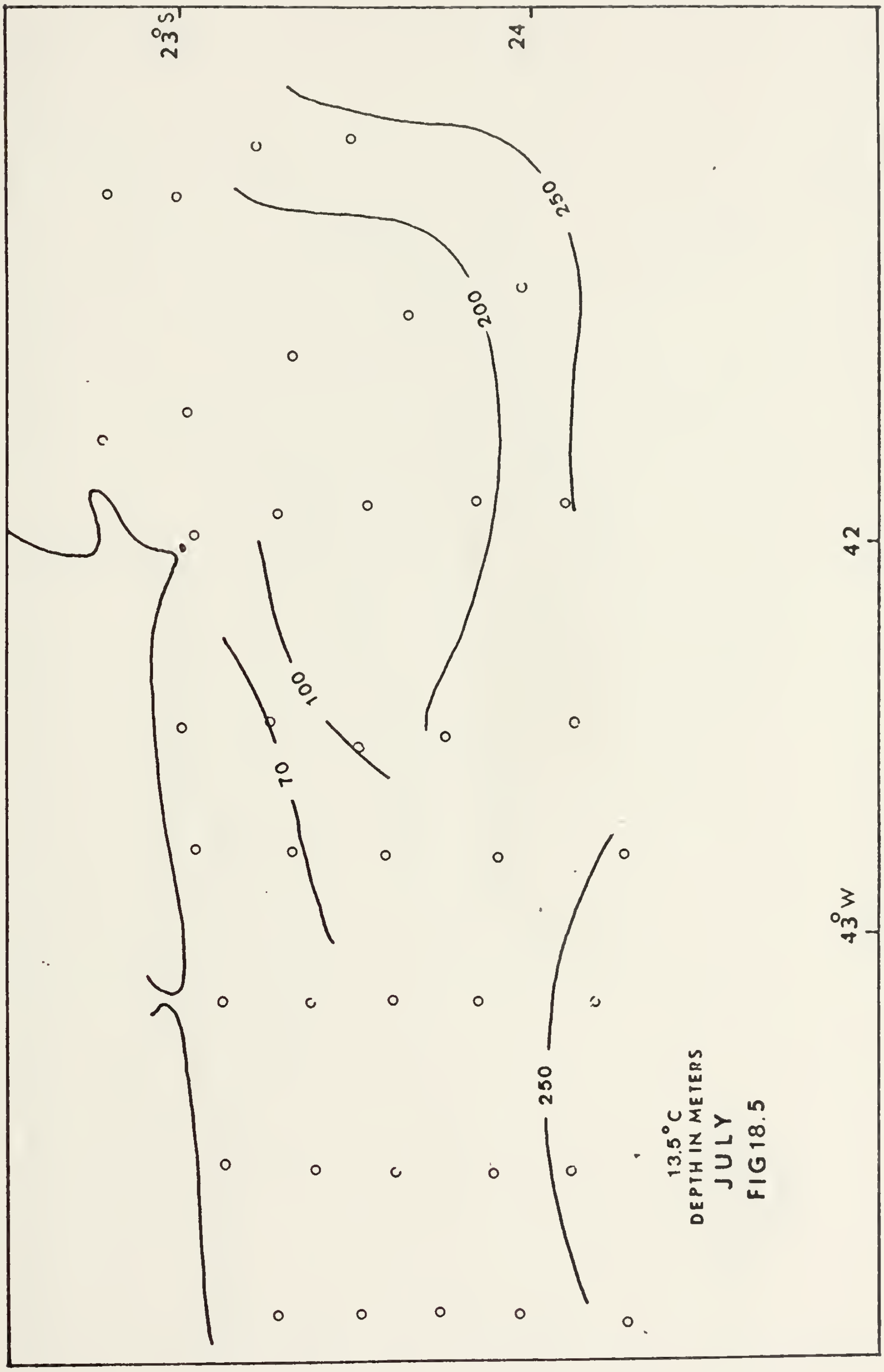
13.5°C
DEPTH IN METERS
FEBRUARY
FIG18.2



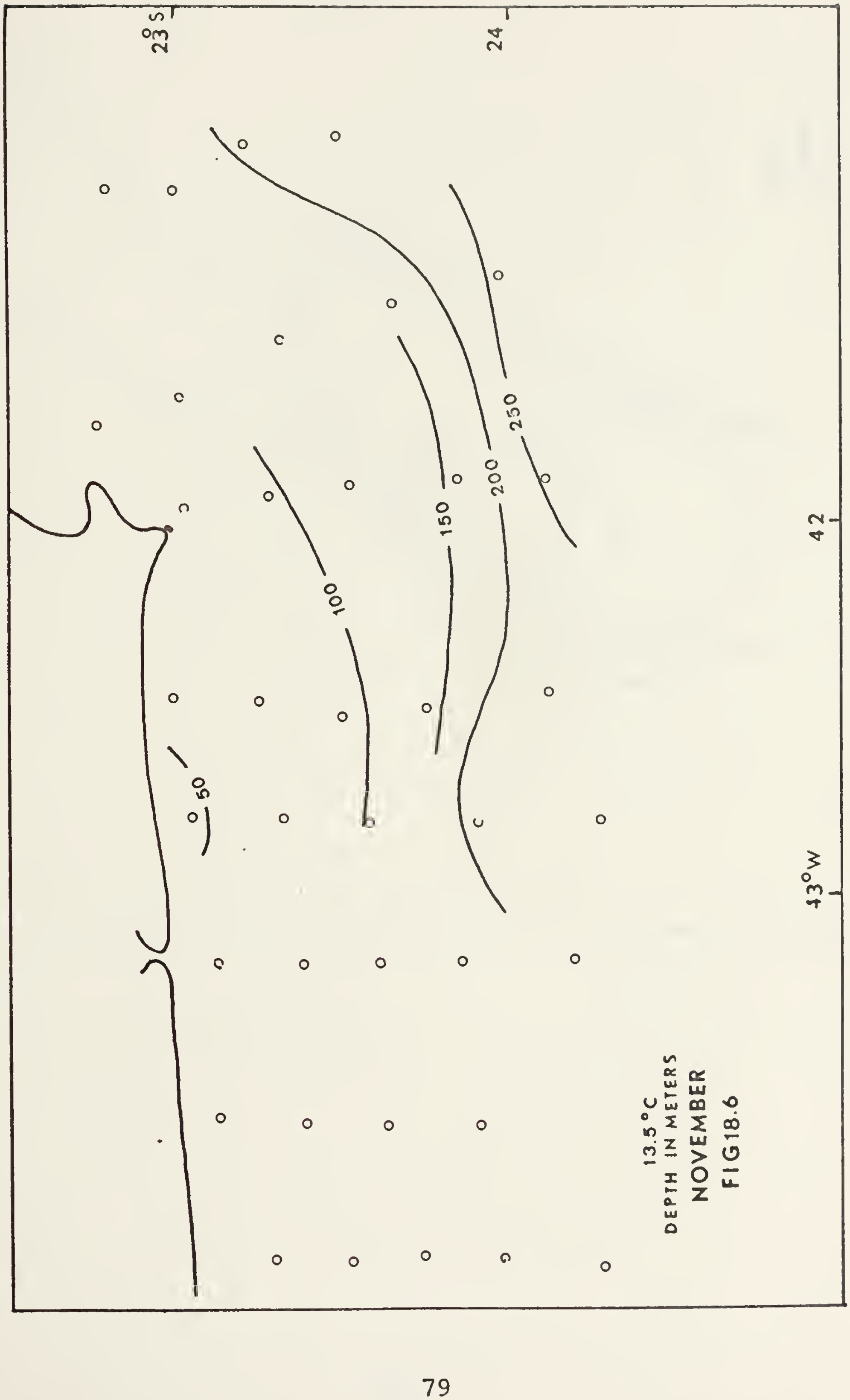
FEBRUARY
FIG 18.3



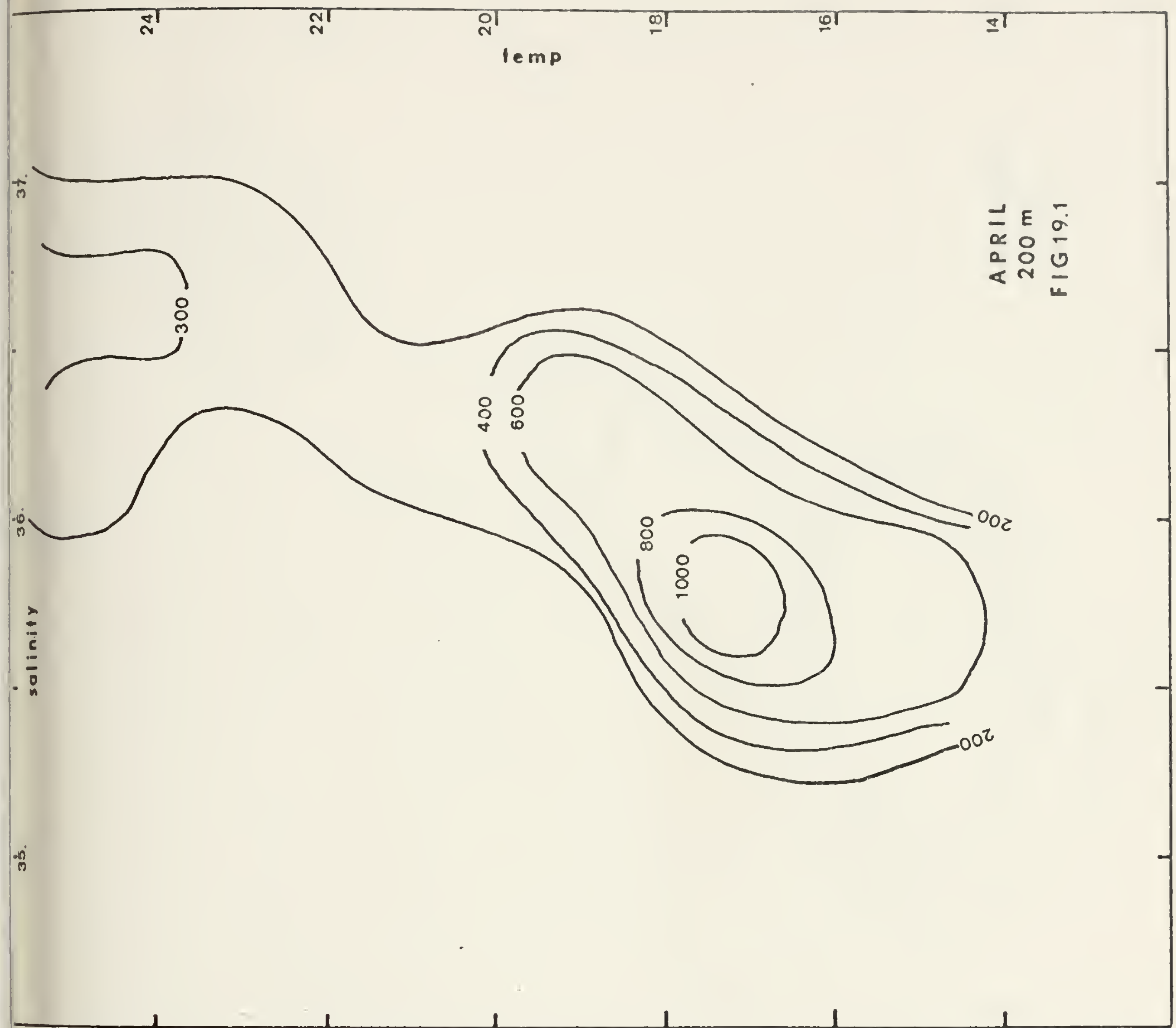
13.5 °C
DEPTH IN METERS
APRIL
FIG184

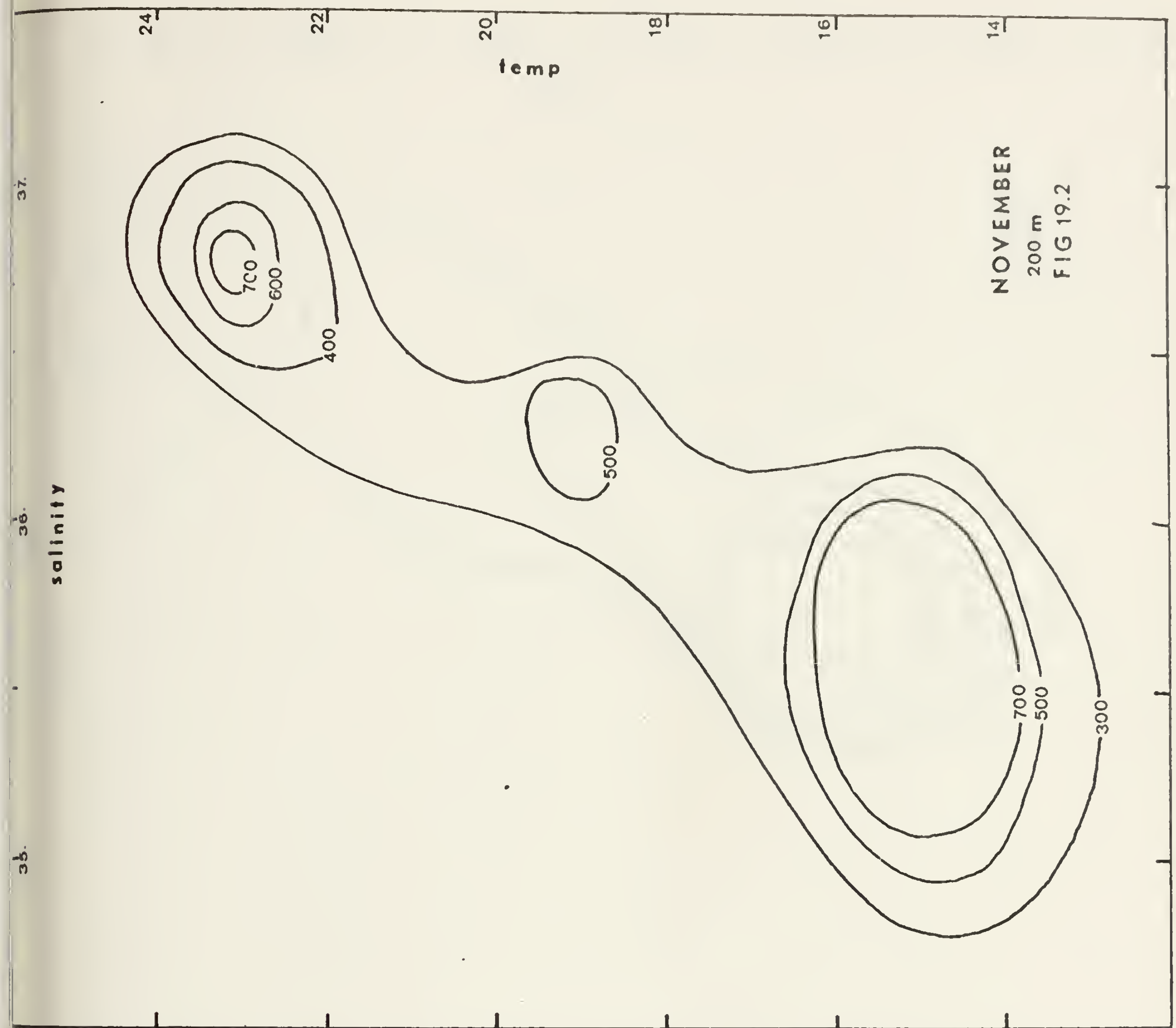


13.5°C
DEPTH IN METERS
JULY
FIG 18.5

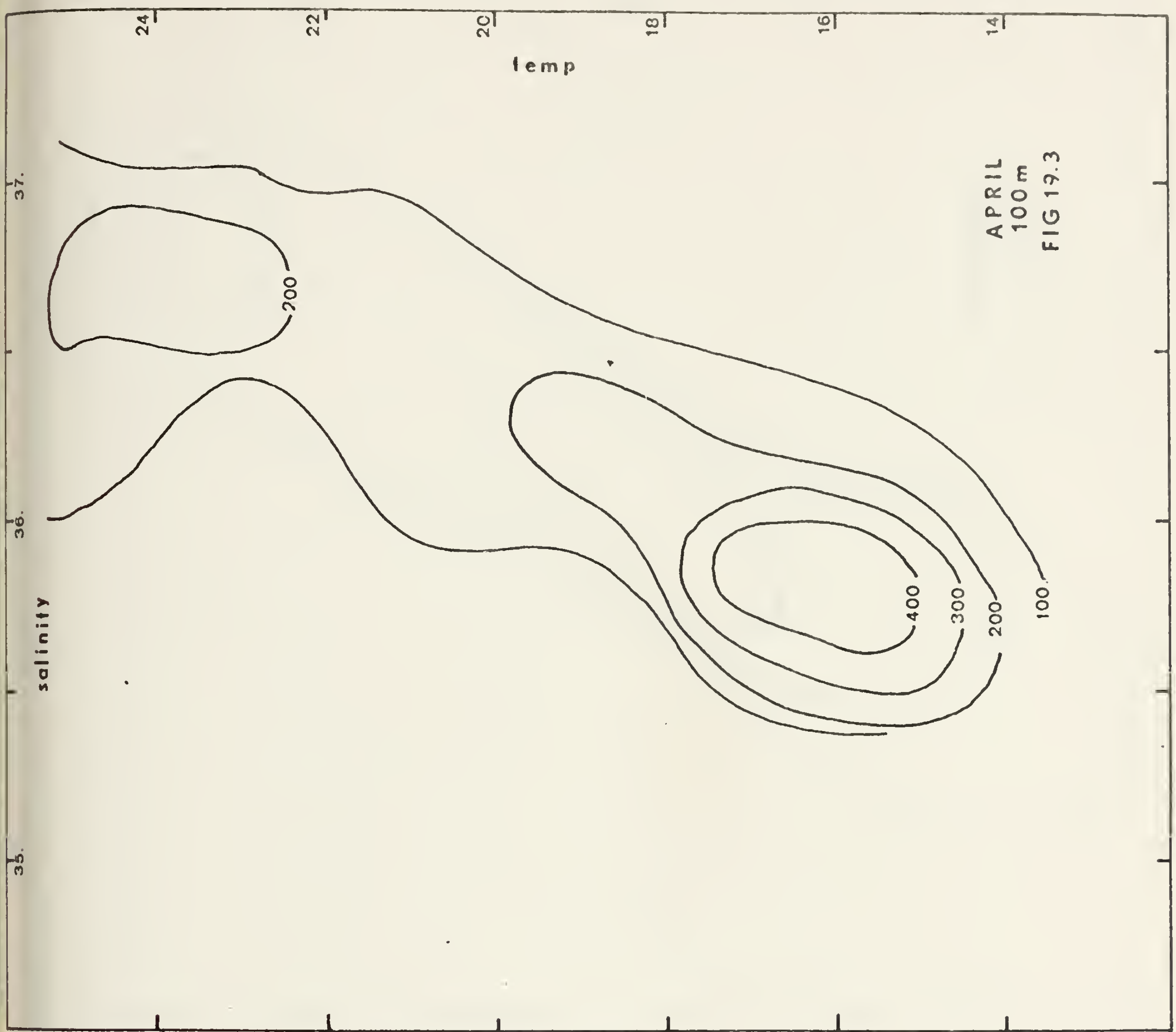


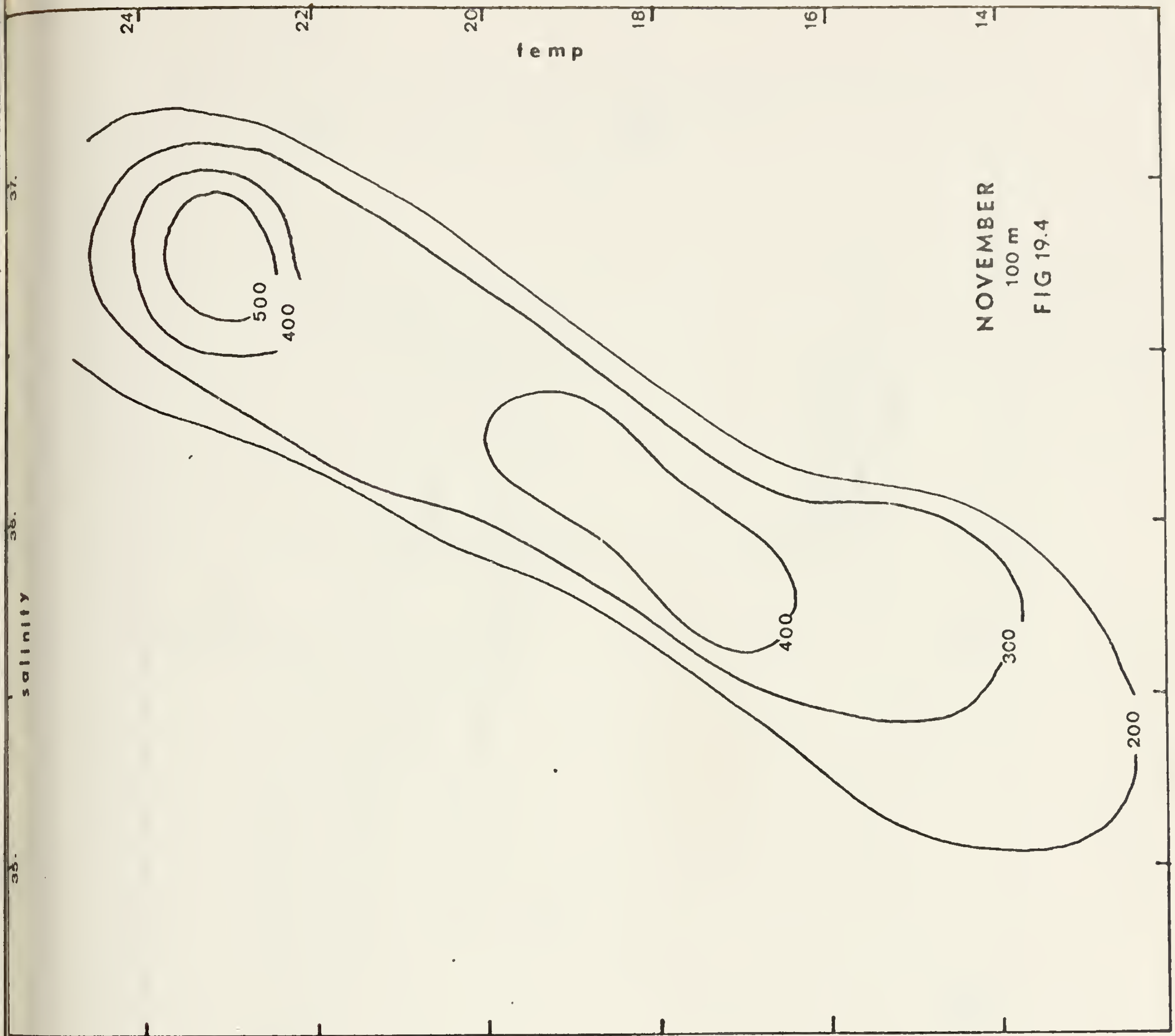
13.5 °C
DEPTH IN METERS
NOVEMBER
FIG18.6


temp
24
22
20
18
16
14
salinity
37.
36.
35.
300
400
600
800
1000
200
200
APRIL
200 m
FIG19.1

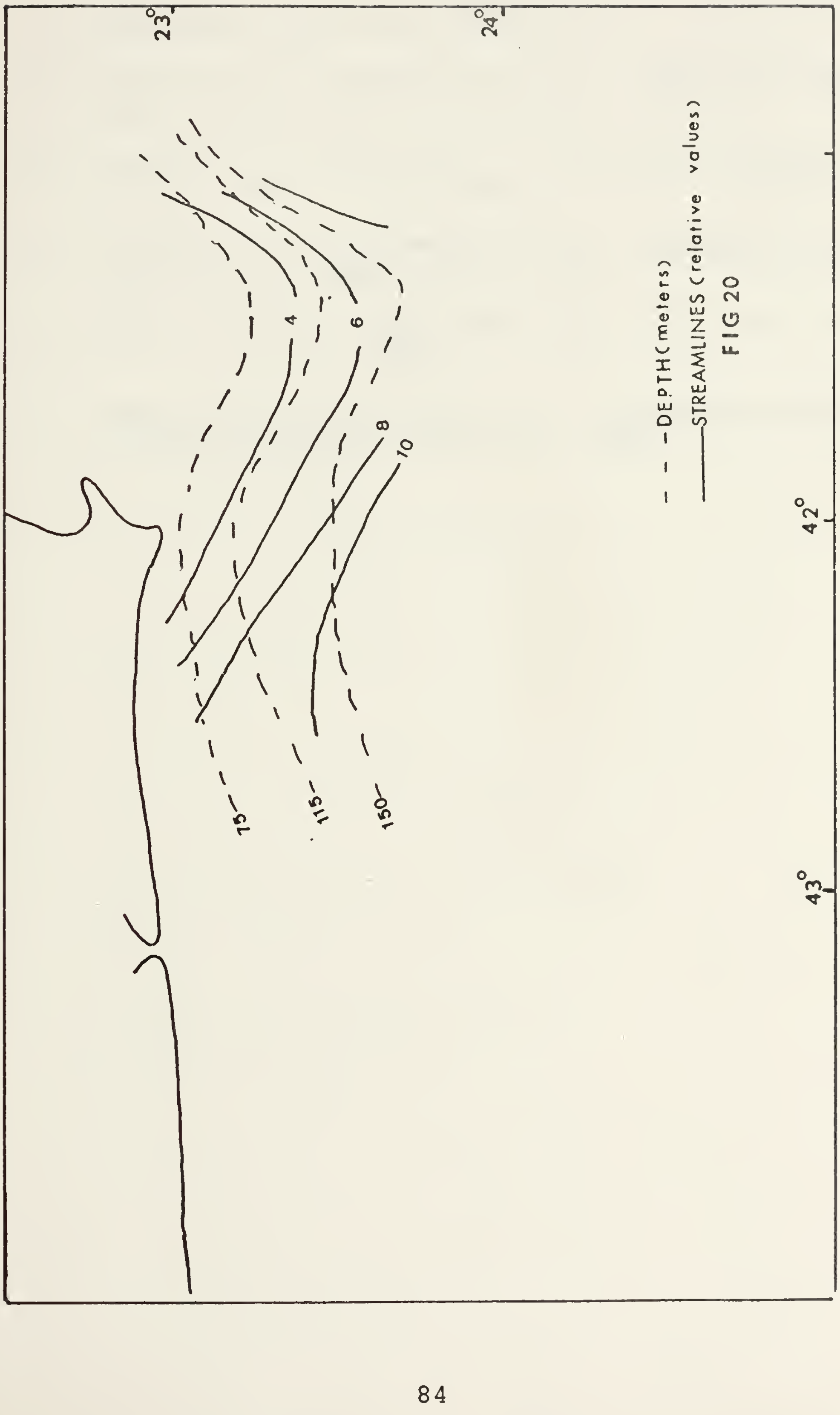


NOVEMBER
200 m
FIG 19.2


temp
24
22
20
18
16
14
salinity
37.
36.
35.
200
400
300
200
100
APRIL
100 m
FIG 19.3



NOVEMBER
100 m
FIG 19.4



23°
24°
42°
43°
- - -DEPTH(meters)
——STREAMLINES (relative values)
4
6
8
10
75
115
150

FIG 20

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Upwelling
Sea-Air Interaction
Sea Level (coastal)
Coastal Currents
Coastal Sea Temperature Changes

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The data at 2 fixed stations along an east-west section of the Brazilian coast near Rio de Janeiro show correlation between observations of wind, sea level, sea temperature and currents. Easterly winds are associated with low temperatures, low sea levels and westward currents. Minimum values of sea level and sea temperature are obtained in the summer and also in the winter. In the Fall the maximum values of sea level and

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sea temperature are observed.

Offshore observations show a maximum incursion of cold water (upwelling) over the continental shelf in winter (July cruise) and summer (November cruise); the minimum incursion of cold water is in the Fall (April cruise).

A geostrophic model shows a net transport in the same direction indicated by the data.